

Chapter 4

Delaware Climate Projections

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Summary

This chapter of the Climate Change Impact Assessment documents projected future changes in temperature- and precipitation-related climate indicators for the state of Delaware. The chapter provides a summary of the data and methods used for this analysis and a detailed discussion of the findings. The findings include projections for average annual and seasonal temperature and temperature extremes; seasonal precipitation, drought, and heavy precipitation; and indicators that combine temperature, precipitation, and/or humidity.

Future projections were developed for two very different types of scenarios, to span a range of possible changes over the coming century. A **lower scenario** represents a future in which people shift to clean energy sources in the coming decades, reducing emissions of carbon dioxide and other greenhouse (heat-trapping) gases that are causing climate to change so quickly. A **higher scenario** represents a future in which people continue to depend heavily on fossil fuels, and emissions of greenhouse gases continue to grow.

Future projections are based on simulations from nine CMIP5 global climate models and four CMIP3 global climate models.^a Most of the projections discussed here are based on the more recent CMIP5 simulations, unless there are important differences between what is simulated by the older CMIP3 versus the newer CMIP5 models.

Data from 14 long-term weather stations in the region are used in this analysis: Bear, Bridgeville,

Dover, Dover AFB, Georgetown, Georgetown Sussex Airport, Greenwood, Lewes, Middletown, Milford, Newark University Farm, Selbyville, Wilmington Porter Reservoir, and Wilmington New Castle County (NCC) Airport. Statistical downscaling of global model projections to each of the 14 weather stations was performed using the Asynchronous Regional Regression Model.

Over the coming century, climate change is expected to affect Delaware by increasing **average** and **seasonal temperatures**.

- By near-century (2020-2039), annual average temperature increases of 1.5 to 2.5°F are projected, regardless of scenario.
- By mid-century (2040-2059), annual average temperature increases under the lower scenario range from 2.5 to 4°F and around 4.5°F for the higher scenario.
- By late-century (2080-2099), annual average temperature is projected to change by nearly twice as much under the higher as compared to lower scenario: 8 to 9.5°F compared to 3.5 to 5.5°F.
- Slightly greater temperature increases are projected for spring and summer as compared to winter and fall.
- The range of spring temperature (between daytime maximum and nighttime minimum temperature) is projected to increase, while the range in fall temperature is projected to decrease.
- The growing season is projected to lengthen, with slightly greater changes in the date of last spring frost as compared to first fall frost.

^a CMIP3 and CMIP5 are two groups of global climate models developed by the Coupled Model Intercomparison Project (CMIP).

Temperature extremes are also projected to change. The greatest changes are seen at the tails of the distribution, in the number of days above a given high temperature or below a given cold temperature threshold. By mid-century, changes under the higher scenario are greater than changes under the lower scenario.

- The number of very cold days (below 20°F), which historically occur on average about 20 times per year, is projected to drop to 15 by 2020-2039, to slightly more than 10 days per year by 2040-2059, and to 10 days per year under the lower scenario and only 3 to 4 days per year under the higher scenario by 2080-2099.

Key Terms and Definitions

Climate indicators – Represent the state of a given environmental condition over a certain area and a specified period of time, such as the mean annual temperature in Delaware for the period 1895-2011 or 2020-2039.

Climate projections – A description of the future climate conditions based on global climate model simulations driven by a range of scenarios describing future emissions from human activities. A climate projection is usually a statement about the likelihood that something will happen over climate time scales (i.e., several decades to centuries in the future) if a given emissions or forcing pathway is followed. In contrast to a prediction (such as a weather prediction), a projection specifically allows for significant changes in the set of boundary conditions, such as an increase in greenhouse gases, which might influence the future climate. As a result, what emerge are conditional expectations (if X happens, then Y is what is expected).

Higher and lower scenarios – Scenarios are used to describe a range of possible futures. Studies of future climate projections are often based on two or more possible future scenarios. In this analysis, the lower scenario represents a future in which people shift to clean energy sources in the coming decades, reducing emissions of carbon dioxide and other greenhouse gases. The higher scenario represents a future in which people continue to depend heavily on fossil fuels, and emissions of greenhouse gases continue to grow.

Observations – Data collected from weather stations, usually daily, using measurement instruments. Data usually consists of temperature and precipitation, but weather stations may also collect data on humidity, wind speed, and other conditions.

Global climate models (GCMs) – Complex, three-dimensional models that incorporate all the primary components of the earth's climate system, including atmospheric and ocean

dynamics. Earlier versions that only modeled the atmosphere and ocean were known as general circulation models. (*See detailed description in Appendix.*)

CMIP3 and CMIP5 – Two groups of global climate model simulations archived by the Coupled Model Intercomparison Project (CMIP). CMIP3 simulations were used in the Third and Fourth Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC). The more recent CMIP5 simulations are used in the Fifth Assessment Report of the IPCC. (*See detailed description in Appendix.*)

Natural climate variability – Variation in seasonal, year-to-year, and even multiyear cycles that can result in wetter or drier, hotter or cooler periods than “average” weather measurements. Most natural climate variability occurs over time scales shorter than 20 to 30 years.

Statistical downscaling – A method used to combine higher resolution observations with global climate model simulations in to obtain local- to regional-scale climate projections. Statistical downscaling models capture historical relationships between large-scale weather features and local climate. (*See detailed description in Appendix.*)

Multi-model or scientific uncertainty – Different models in a climate analysis may yield different results. In this report, the range of results, or outputs, from multiple models is expressed in the black “whiskers” (error bars) shown on the bar graphs, while the colored bar represents the multi-model mean. (*See detailed description in Appendix.*)

Standard deviation of temperature – Assesses the day-to-day variability in daily maximum and minimum temperatures.

Temperature – Air temperatures over land surface, typically recorded at a height of 2 meters, in degrees Fahrenheit as °F.

- The number of very hot days (over 100°F), which historically occur less than once each year, is projected to increase to 1 to 3 days per year by 2020-2039, 1.5 to 8 days per year by 2040-2059, and by 3 and 10 days per year under the lower and 15 to 30 days per year under the higher scenario by 2080-2099.
- Heat waves are projected to become longer and more frequent, particularly under the higher as compared to lower scenario and by later compared to earlier time periods. For example, heat waves with at least 4 consecutive days warmer than the 1-in-10 historical average are expected to occur on average between 1 to 3 times per year by 2040-2059,

Precipitation – Includes rain and snow, typically recorded as cumulative amount over a given time period ranging from a day to a year, in inches.

Temperature and precipitation extremes – Extremes can be measured using fixed thresholds (e.g., days per year over 100°F) or using percentiles (e.g., number of days colder than the coldest 1% of days).

Maximum temperature – The highest temperature value in a given time period (daily, seasonal, or annual). Unless otherwise stated, all daily maximum temperatures in this report refer to values recorded within a 24-hour period, usually (but not always) occurring in the afternoon (also described as daytime temperatures).

Minimum temperature – The lowest temperature value in a given time period (daily, seasonal, or annual). Unless otherwise stated, all daily minimum temperatures in this report refer to values recorded within a 24-hour period, usually occurring at night (also described as nighttime temperatures).

Temperature range – The range between highest and lowest temperature value in a given period (daily, seasonal, or annual).

Heat wave events – A period of prolonged, unusual heat. There is no single standard definition of a heat wave. Different measures can be used to assess the frequency and severity of heat events, such as the length of consecutive days with maximum daytime temperatures exceeding a specific threshold temperature (e.g., 90°F, 95°F, 100°F). Another definition of an extreme heat wave is at least four consecutive days during which average temperatures (daytime plus nighttime temperatures) exceed the historical 1-in-10 year event.

Growing season – The “frost-free” period between the last frost in spring and the first frost in fall or winter, defined as the last and first time that nighttime minimum temperature falls below 32°F.

Cooling degree-days and heating degree-days – An indicator of energy demand for heating and cooling. This represents demand for electricity in the summer (for air conditioning) and natural gas or oil in the winter (for space heating). Degree-days are typically calculated as the cumulative number of hours per year above (for cooling) or below (for heating) a given temperature threshold. For this analysis the threshold value is 65°F.

Precipitation intensity – Total precipitation over a season or year, divided by the number of wet days (where wet days are defined as days with more than 0.01 inches of rain in 24 hours) that occurred in that same season or year. Higher values of precipitation intensity tend to suggest that, on average, precipitation may be heavier on any given wet day; lower values, that precipitation may be lighter on average.

Annual dry days – The number of days per year with no (or trace) precipitation (falling as either rain or snow).

Standardized Precipitation Index (SPI) and Palmer Drought Severity Index (PDSI) – Measurements of drought with negative values indicating dry (drought) conditions and positive values indicating wet conditions.

Dew point temperature – The temperature to which the air must be cooled to condense the water vapor it contains into water.

Relative humidity – The percentage of water vapor actually present in the air compared to the greatest amount of water vapor the air could possibly hold at the same temperature.

Heat index – A measurement that combines temperature and humidity, which affects evaporation and cooling. Sometimes referred to as the “apparent temperature”, the Heat Index is a measure of how hot it really feels to the human body.

and an average of 3 times per year under a lower and 10 times per year under the higher scenario by 2080-2099.

- Daytime summer heat index (a measure of how hot it feels, based on maximum temperature and average humidity) is projected to increase by approximately twice as much as projected changes in maximum temperature alone, due to the nonlinear relationship between heat index, temperature, and humidity.

Average precipitation is projected to increase an estimated 10 percent by late-century, consistent with projected increases in mid-latitude precipitation in general. CMIP3 and CMIP5 models do not show the same seasonality: CMIP3 shows increases in winter, spring, and summer, while CMIP5 simulations show increases primarily in winter alone.

Rainfall extremes are also projected to increase. By late-century, nearly every model simulation shows projected increases in the frequency and amount of heavy precipitation events. This increase is consistent over a very broad range of definitions of “heavy precipitation”: accumulations ranging from 0.5 to 8 inches over anywhere from 1 day to 2 weeks.

All simulations show large increases in potential evapotranspiration and in the number of hot and dry days per year. Smaller to no significant changes are projected for relative humidity and for the number of cool and wet days per year.

There is *greatest certainty* in projected increases in annual and seasonal temperatures, high temperatures, increased evaporation, precipitation intensity, and the frequency of heavy precipitation, all of which show greater increases under the higher as compared to lower scenario and by late-century as compared to more near-term projections. There is *moderate certainty* in projected changes in cold temperatures and an increase in annual precipitation on the order of 10 to 20 percent. There is *less certainty* in projected changes in seasonal precipitation, specifically which seasons are likely to see

the greatest increases in precipitation and in moderate precipitation amounts (0.5 to 1 inch in 24 hours).

List of Graphs for Temperature and Precipitation Indicators

Future projections are summarized for three future time periods, relative to a historical baseline of 1981-2010: near-century (2020-2039), mid-century (2040-2059) and late-century (2080-2099). The results are discussed in the following sections. A complete list of graphs for all indicators can be found in the Appendix.

TEMPERATURE Annual and Seasonal

- Maximum temperature
- Minimum temperature
- Average temperature
- Temperature range (average maximum minus average minimum)
- Standard deviation of maximum and minimum temperature

Extremes

- Cold nights: days per year with minimum temperature below 20°F and 32°F or below the 1st and 5th percentile of the historical distribution
- Hot days: days per year with maximum temperature above 90, 95, 100, 105, and 110°F or above the 95th and 99th percentile of the historical distribution
- Warm nights: days per year with minimum temperature above 80, 85, and 90°F
- Number of heat wave events lasting 4 or more days (as defined by Kunkel et al., 1999¹)
- Longest stretch of days with maximum temperature over 90, 95, and 100°F

Other

- Date of last frost in spring and first frost in fall
- Length of frost-free growing season
- Annual cooling degree-days
- Annual heating degree-days

PRECIPITATION

Annual and Seasonal

- Seasonal and annual cumulative precipitation
- Cumulative precipitation for 3-, 6-, and 12-month running means, beginning in each month of the year

Extremes

- Precipitation intensity: annual precipitation divided by the number of wet days per year
- Heavy precipitation days: days per year with cumulative precipitation exceeding 0.5, 1, 2, 3, 4, 5, 6, 7, and 8 inches in 24 hours
- Extreme events: amount of precipitation falling in the wettest 1, 5, and 14 days in 1, 2, and 10 years
- Number of future events exceeding the historical wettest 2, 4, and 7 days

Other

- Total number of dry days each year (precipitation < 0.01 inches)
- Longest dry period
- Standardized Precipitation Index (a measure of wetness and drought)

HUMIDITY and HYBRID INDICATORS

Annual and Seasonal

- Dew point temperature
- Relative humidity
- Summer heat index

Other

- Percentage of precipitation falling as rain versus snow
- Number of hot and dry days per year (precipitation < 0.01" and maximum temperature > 90°F)
- Number of cool and wet days per year (precipitation > 0.01" and maximum temperature < 65°F)

4.1. Background

Since the Industrial Revolution, atmospheric levels of heat-trapping gases such as carbon dioxide (CO₂) and methane (CH₄) have been rising due to emissions from human activities. The main source of heat-trapping gases is the combustion of fossil fuels such as coal, oil, and natural gas.^{2, 3} Other activities, such as agriculture, wastewater treatment, and extraction and processing of fossil fuels, also produce carbon dioxide, methane, nitrous oxide, and other gases.⁴

CO₂ and other heat-trapping gases exist naturally in the atmosphere. However, artificially increasing the amounts of these gases in the atmosphere affects the energy balance of the planet. As levels increase, more of the heat given off by the earth that would otherwise escape to space is trapped within the earth's climate system. This extra heat increases the temperature and the heat content of the atmosphere, ocean, and land surface.

Over short timescales, of years to more than a decade, natural variability has a strong effect on global and regional temperatures. Some patterns of natural variability increase the ocean's share of the heat uptake compared to the atmosphere's. Over the last 150 years, average surface temperatures in the Northern Hemisphere have risen by 1.5°F. At the global scale, each decade has successively been warmer than the decade before. The heat content of the ocean has increased by more than 20 times that of the atmosphere.^{5, 6}

4.1.1. Observed and Projected Future Change

In the United States, average temperature has increased by 1.5°F over the last century, with most of the increase occurring in the last 30 years.⁷

Warmer temperatures are driving many changes in average climate conditions in the United States and around the world. Observed changes highlighted by the Third U.S. National Climate Assessment include:

- More frequent heavy precipitation events, particularly in the Northeast and Midwest
- Increasing risk of heat waves, floods, droughts, and wildfire risk in some regions
- Decreases in Arctic sea ice, earlier snow melt, glacier retreat, and reduced lake ice
- Stronger hurricanes, rising sea level, and warming oceans
- Poleward shifts in many animal and plant species, as well as a longer growing season

In the past, climate variations were caused entirely by natural forces. These include changes in amount of energy the earth receives from the sun, natural cycles that exchange heat between the ocean and atmosphere, or the cooling effects of dust clouds from powerful volcanic eruptions, amplified by natural feedbacks within the earth-ocean-atmosphere system. Today, however, the climate is being altered by both natural and human causes.⁸ Recent studies have concluded that human influence, specifically the increases in emissions of CO₂ and other heat-trapping gases from human activities, is responsible for most of the warming over the last 150 years, and as much as all of the warming over the last 60 years.^{9,10,11}

Over the coming century, climate will likely continue to change in response to both past and future emissions of heat-trapping gases from human activities.¹² At the global scale, average temperature increases between 2°F and 9°F are expected by late-century, accompanied in many

regions of the United States by increases in extreme heat and heavy precipitation events. These future projections are consistent with observed trends.^{13, 14}

Future changes depend on heat-trapping gas emissions from human activities. For many impacts, higher emissions are expected to result in greater amounts of change; lower emissions, in comparatively smaller amounts of change. The 2011 U.S. National Research Council report “Climate Stabilization Targets” quantified many of the impacts that would be expected to increase per degree of global warming. For example, each degree-Celsius (almost 2°F) increase in global temperature might be expected to:

- Shift the amount of precipitation that falls in many regions around the world by 5 to 10 percent
- Increase the amount of rain falling during heavy precipitation events by 3 to 10 percent
- Shift the amount of streamflow and runoff in river basins by 5 to 10 percent (with increases in the northeastern United States and decreases in the southwestern United States)
- Shrink annual average Arctic sea ice area by 15 percent (by 25 percent, for the September minimum)
- Reduce yields of common crops, including wheat and maize, by 5 to 15 percent worldwide
- Increase the area burned by wildfire in the western United States by 200 to 400 percent

4.1.2. Implications for Delaware

Delaware’s climate – together with that of the rest of the United States – is already changing. What might the future hold?

Future climate depends on the impact of human activities on climate, and the sensitivity of climate to those emissions. This report describes projected changes in Delaware’s climate under two possible scenarios: a higher scenario in which fossil fuels continue to provide most of humankind’s energy

needs, and a lower scenario in which global carbon emissions peak within a few decades, then begin to decline.

Future projections are based on simulations from two groups of global climate models: the older models used in the 2007 Northeast Climate Impacts Assessment, and the newer set of models used in the upcoming Third U.S. National Climate Assessment.

Global model projections were translated down to the local scale using a statistical downscaling model. This model relates modeled variability and changes in large-scale climate to observed conditions at 14 long-term weather stations in Delaware, then uses this relationship to estimate how the regional manifestations of global climate change might affect local conditions in the future.

Assessing the potential impacts of climate change on a given location is a challenging task. Future projections are uncertain, due to the difficulties in predicting human behavior; understanding the response of the earth's climate to heat-trapping gases produced by human activities; and predicting the variability of natural cycles within the earth system that have a strong influence on local climate.

Although challenging, it is important to assess climate impacts because the information generated can be valuable to long-term planning or policies. For example, projected changes in heating- or cooling degree-days can be incorporated into new building codes or energy policy. Shifts in the timing and availability of streamflow can be used to redistribute water allocations or as incentive for conservation programs. Projected changes in growing season and pest ranges can inform crop research and agricultural practices.

The information generated by this analysis, and summarized in this report, is intended to inform such studies for the state of Delaware and relevant sectors by providing state-of-the-art climate projections that can be incorporated into future planning.

4.2. Data and Methods

A detailed discussion of the methods and the assessment framework used for the climate projections analysis can be found in the Appendix. The detailed methodology section describes the specific data sets and methods used to assess projected changes in Delaware climate in response to human-induced global climate change. These datasets, models, and methods include future scenarios, global climate models, long-term station records, and a statistical downscaling model.

4.2.1. Global Climate Models

Global climate models (GCMs) are complex, three-dimensional models of the atmosphere, oceans, and earth's surface that are used to better understand historical climate as well as to study how future climate might change in response to human emissions of CO₂ and other heat-trapping gases. The climate projections produced by this analysis are based on simulations from four older CMIP3 models and nine newer CMIP5 models. All of the bar charts shown in this chapter show the all-model average (colored bar), as well as the range of values simulated by the different models (thin black lines, or whiskers). Unless otherwise indicated, the results shown in this report are based on the newer CMIP5 simulations only. (See Appendix for complete description of models used in this analysis.)

4.2.2. Statistical Downscaling Model

This project used the statistical Asynchronous Regional Regression Model. It was selected because it is able to resolve the tails of the distribution of daily temperature and precipitation to a greater extent than other more commonly used methods, but is less time-intensive and therefore able to generate more outputs as compared to a high-resolution regional climate model.

4.2.3. Station Observations

This project used long-term station data from the Global Historical Climatology Network and the National Climatic Data Center Co-op Observing Network, supplemented with additional station data provided by the Delaware State Climatologist. All station data was quality controlled to remove questionable data points before being used to train the statistical downscaling model. Projected future changes are consistent across all 14 stations; unless otherwise indicated, plotted values in this report correspond to the average value across the 14 stations (**Figure 4.1**).

To train the downscaling model, the observed record must be of adequate length and quality. After the quality control and filtering process was complete, there were 14 usable stations for Delaware for maximum and minimum temperature and precipitation.

4.2.4. Higher and Lower Scenarios

Future scenarios depend on a myriad of factors, including how human societies and economies will develop over the coming decades; what technological advances are expected; which energy sources will be used in the future to generate electricity, power transportation, and serve industry; and how all these choices will affect future emissions from human activities.

The Intergovernmental Panel on Climate Change (IPCC) has released two families of future scenarios: the 2000 Special Report on Emission Scenarios (SRES) and the 2010 Representative Concentration Pathways (RCP). In contrast to the SRES scenarios, RCPs are expressed in terms of CO₂ concentrations in the atmosphere, rather than direct emissions. This analysis uses the higher and lower scenarios from each family: RCP 8.5 (higher) and 4.5 (lower) concentration pathways and SRES A1fi (higher) and B1 (lower) emission scenarios.

- The higher scenario represents a world with fossil fuel-intensive economic growth. In these scenarios, emissions

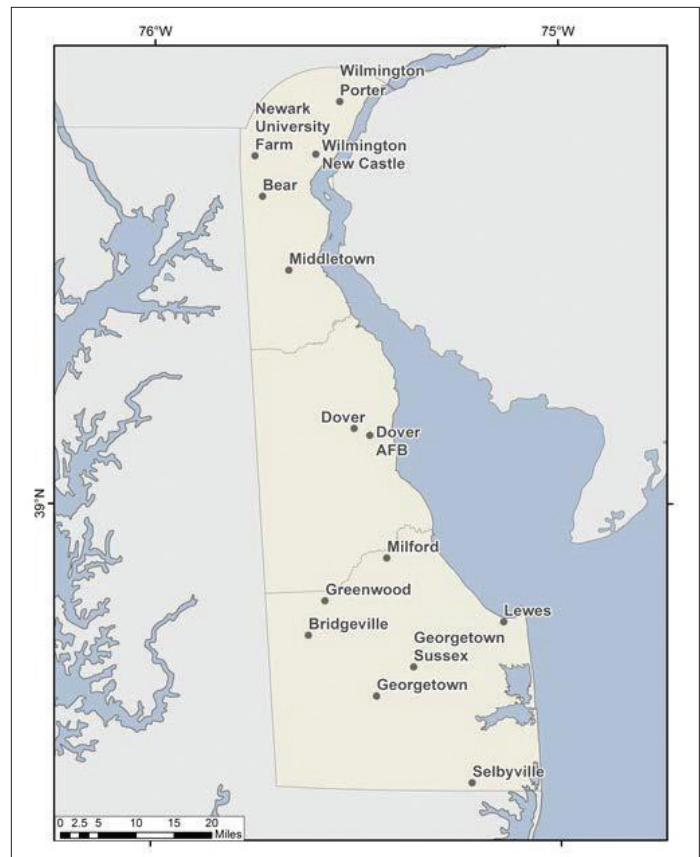


Figure 4.1. This report generated future projections for 14 weather stations in Delaware with long-term historical records. Weather stations that did not have sufficiently long and/or complete observational records to provide an adequate sampling of observed climate variability at their locations were eliminated from this analysis.

continue to increase and atmospheric CO₂ concentrations reach nearly 1,000 parts per million by 2100, more than triple preindustrial levels of 280 ppm.

- In the lower scenario, a shift to less fossil fuel-intensive industries and the introduction of clean and resource-efficient technologies cause emissions of greenhouse gases to peak around mid-century and then decline. Atmospheric CO₂ concentrations approximately double by 2100 compared to preindustrial levels.

In the near term, most projections do not show a great difference between the higher versus lower scenario. This is because the climate is currently responding to the greenhouses gases already in the atmosphere. By the second half

of the century, however, there is a noticeable difference between projected changes for most climate indicators under a higher as compared to a lower scenario. The difference is due to the much greater concentrations of greenhouse gases if emissions continue to increase. The substantial difference between the higher and lower scenario used here provides a good illustration of the potential range of changes that could be expected over the coming century, and how much these depend on future emissions and human choices.

4.2.5. Uncertainty

Uncertainty in future climate change projections at the global to regional scale is primarily due to three different causes: (1) *natural variability* in the climate system, (2) *scientific uncertainty* in predicting the response of the earth's climate system to human-induced change, and (3) *scenario uncertainty* in predicting future energy choices and hence emissions of greenhouse gases from human activities.¹⁵

In the near term – over timescales of years to one or two decades – *natural variability* is the most important source of uncertainty. In developing climate projections, this uncertainty can be addressed by always averaging or otherwise sampling from the statistical distribution of future projections over a climatological period – here, 20 years.

By mid-century, *scientific uncertainty* is the largest contributor to the range in projected temperature and precipitation change. This can be addressed by using multiple global climate models that simulate the response of the climate system to human-induced change in slightly different ways. The climate models used in this analysis cover a range of climate sensitivity.

By the end of the century, *scenario uncertainty* is most important for temperature projections, while scientific (or model) uncertainty continues as the dominant source of uncertainty in precipitation. Scenario uncertainty can be addressed by comparing climate projections for multiple

futures: for example, a “higher” future in which the world continues to depend on fossil fuels as the primary energy source (RCP 8.5), as compared to a “lower” future focusing on sustainability and conservation (RCP 4.5).

It is important to note that *scenario uncertainty* is very different, and entirely distinct, from *scientific uncertainty*. While scientific uncertainty can be reduced through coordinated observational programs and improved physical modeling, scenario uncertainty reflects our fundamental inability to predict future changes in human behavior. It can be reduced only by the passing of time, as societal choices can eliminate or render certain options less likely. In addition, scientific uncertainty is often characterized by a normal statistical distribution, in which a central value is more likely than the outliers. Scenario uncertainty, however, depends on societal choices for economic development, future technologies, and other factors that influence the rate of greenhouse gas emissions from human activity. Hence, scenario uncertainty cannot be considered to be a normal statistical distribution. Rather, the consequences of a lower versus a higher emissions scenario must be considered independently to isolate the role that human choices are likely to play in determining future impacts.

The Data, Models, and Methods section in the Appendix of the Assessment includes a more detailed discussion of types and sources of uncertainty and how they are addressed in climate modeling.

4.3. Temperature-Related Indicators

In the future, average temperature and temperature-related indicators across the state of Delaware are expected to increase. Year-to-year variations in temperature are primarily the result of natural variability, or what we often call “weather.” Long-term changes, over timescales of 30 years or more, are expected to be primarily driven by increases in global temperature.

The magnitude and rate of global climate change depend on the amount of human emissions, as well as on the sensitivity of the earth's climate system to those emissions. Impacts on Delaware's climate due to global climate change will be modified by local factors, including topography (such as the proximity of the state to the ocean), small-scale feedback processes (such as changes in the type of vegetation that grows in Delaware as climate changes), and land use (including conversion of forests to suburbs, or fields to forests).

This chapter summarizes the changes in temperature and temperature-related secondary indicators that are projected to occur in response to global climate change. Projected changes are consistent across all 14 stations; unless otherwise indicated, plotted values correspond to the 14-station average, across the state.

Projections shown in figures and discussed in the text are averaged across all of the latest generation of CMIP5 climate models for individual scenarios: higher (RCP 8.5) and lower (RCP 4.5). All figures include the scientific uncertainty that results from using multiple climate models. For CMIP3 climate models (not shown here), scientific uncertainty was defined by the difference between the highest and lowest model projection for each scenario and time period. For CMIP5 climate models, because there are more of them, scientific uncertainty was defined by the standard deviation of the all-model ensemble unless the distribution was significantly non-normal, or skewed, in which case the highest or lowest model projection was used to define the range instead.

4.3.1. Annual and Seasonal Temperatures

In the future, **annual average temperature** is expected to continue to increase. Over the next few decades, projected temperature changes are expected to be similar regardless of the scenario followed over that time. There is no significant difference between temperature projections from different scenarios over the short term for two reasons. First, it takes some time for the climate system to respond to differences in emissions.

Second, emissions among different scenarios are not very different over the short term. This is because of the lags in our socioeconomic and energy systems: installations of fossil fuel or renewable energy take years to design and build, and are typically used for decades. None of the scenarios considered here envision a world in which all fossil fuel use could be eliminated within a decade or two. For these two reasons, the majority of the changes that will happen over the next few decades are the result of heat-trapping gas emissions that have already built up in the atmosphere or are already entailed by our existing infrastructure.

By mid-century, temperature increases are greater under the higher scenario versus the lower, although the scientific uncertainty range (i.e., the temperature change projected by a given model) still overlaps (**Figure 4.2**). By late-century, the multi-model uncertainty range for the higher versus the lower scenario does not overlap: in other words, even the smallest projected change in temperature under the higher scenario is greater than the largest projected change under the lower scenario. Temperature increases are also greater for later time periods as compared to earlier ones. By 2020-2039, annual maximum (daytime) temperature is projected to increase by an average of 2 to 2.5°F and annual minimum (nighttime) temperature by an average of 1.5 to 2.5°F across all scenarios. By mid-century 2040-2059, increases under the lower scenario range from 2.5 to 4°F for maximum temperature and 2 to 3.5°F for minimum temperature. Under the higher scenario, increases average 4.5°F for both maximum and minimum temperature. By late-century 2080-2099, projected temperature changes are nearly twice as great under the higher as compared to lower scenario. Maximum temperature increases by 3.5 to 5.5°F under the lower and 8 to 9.5°F under the higher scenario. Minimum temperature increases by 3 to 5°F under the lower and 8.5 to 9.5°F under the higher scenario.

Seasonal temperatures are also projected to increase, sometimes at different rates than the annual average. In general, projected increases for spring and summer are greater than the increases

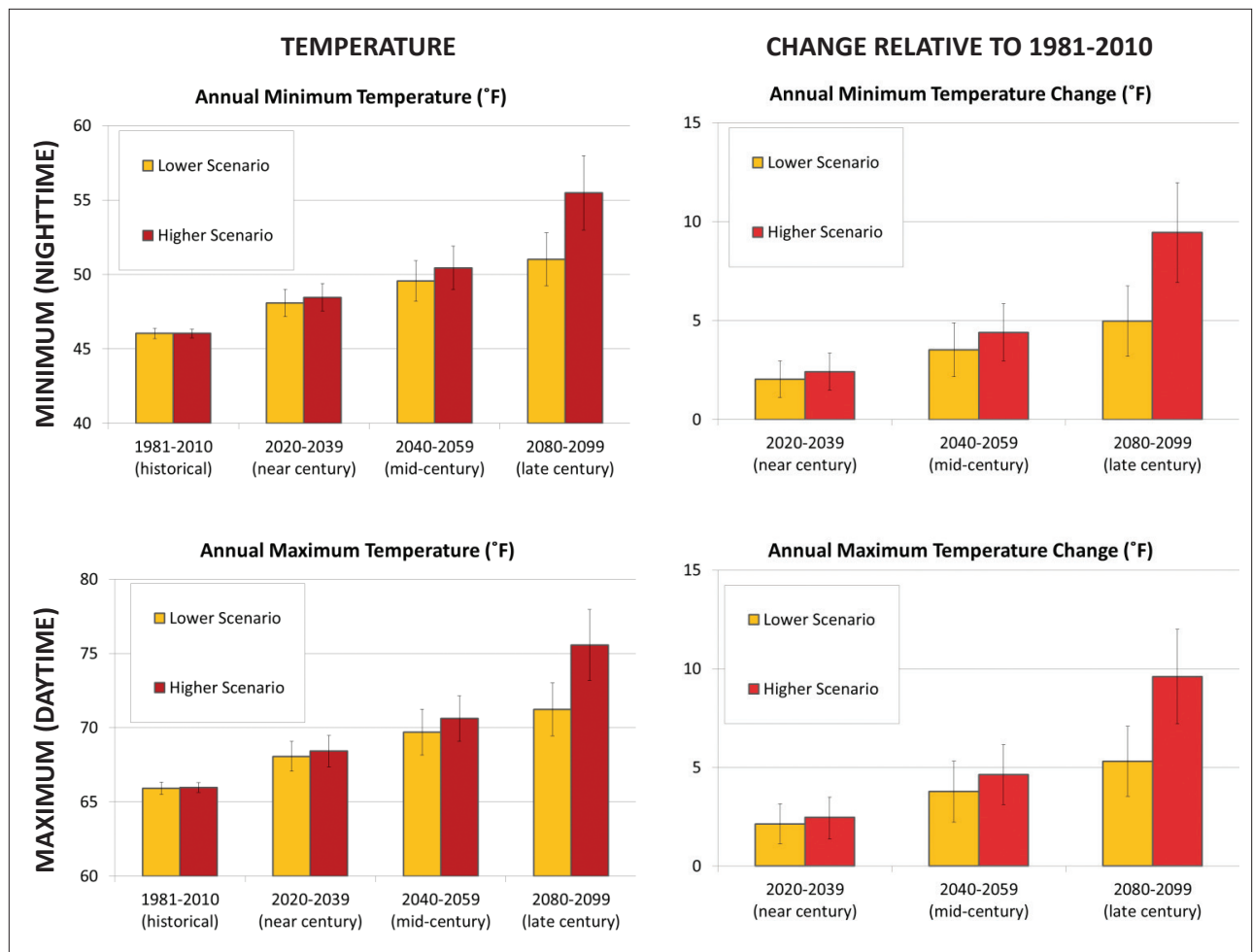


Figure 4.2. Projected absolute (left) and change in (right) **annual maximum (daytime) and minimum (nighttime) temperature** compared to 1981-2010 average values. Changes are the average for the state of Delaware, based on individual projections for 14 weather stations. The black “whiskers” indicate the range of scientific uncertainty that results from using multiple climate models.

projected for fall and winter (**Figure 4.3**). By late-century, for example, spring temperature is projected to increase by about 4 to 6°F under the lower and 7 to 11°F under the higher scenario, while summer temperature is projected to increase by 3.5 to 8°F under the lower and 7 to 15°F under the higher scenario. Fall and winter changes are projected to be smaller: 2 to 5°F under the lower and 6 to 10°F under the higher scenario in fall, and 3.5 to 4°F under the lower and 6.5 to 8°F under the higher scenario in winter.

For both seasonal and annual temperature, the increases simulated by CMIP5 models are generally higher than those simulated by CMIP3 models (not shown). This difference may be due to a greater number of models in CMIP5 as compared to CMIP3, and therefore a larger

sample size of projected changes. It may also reflect different processes occurring within the models, because the CMIP5 models used in this analysis represent newer and more complex versions of CMIP3 models. Comparing simulations for seasonal temperature, it appears that the SRES A1fi and RCP 8.5 scenarios (both higher) are generally close, with RCP 8.5 (higher) being slightly higher than A1fi in all seasons. In contrast, the SRES B1 and RCP 4.5 (lower) scenarios are nearly identical in winter and spring, but extremely different in summer and fall. SRES B1 multi-model average projections and even the multi-model range are significantly smaller (by more than 3°F) than RCP 4.5 in summer and fall. This suggests that there may be different processes at work in driving summer and fall temperature change in the CMIP5 models compared to CMIP3.

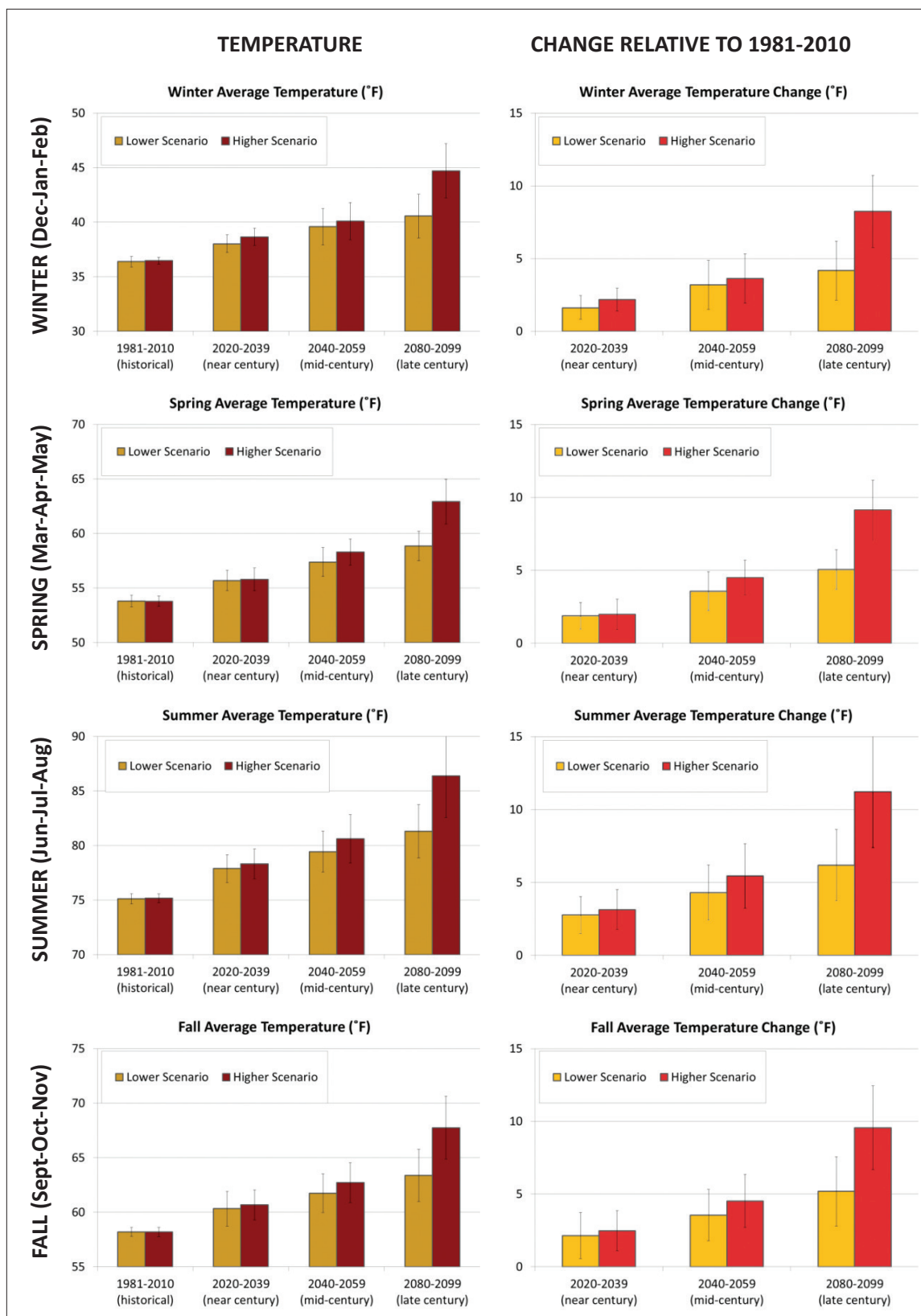


Figure 4.3. Projected absolute value (left) and increase (right) in **seasonal average temperature** compared to 1981-2010 for winter (Dec-Jan-Feb), spring (Mar-Apr-May), summer (Jun-Jul-Aug), and fall (Sept-Oct-Nov). Greater changes are projected for spring and summer as compared to winter and fall. Changes are the average for the state of Delaware, based on individual projections for 14 weather stations. Black “whiskers” indicate the range of scientific uncertainty from multiple climate models.

Historical temperature range is smallest for winter (averaging around 17°F) and largest for spring (around 21°F). The **range of temperature** (the difference between the average maximum and minimum temperature for the season) may be changing in spring and fall, but not in winter or summer. For example, increases in minimum temperature tend to be smaller by about 1°F in spring and fall as compared to projected increases in maximum temperature for those seasons (not shown). For winter and summer, changes in maximum and minimum temperature are similar.

for winter and summer are inconsistent, with some models projecting an increase and others, a decrease. For fall, models project either no change or a decrease in temperature range. Projected changes in annual temperature range are negligible (not shown).

The **standard deviation of temperature** is a different type of measure; it assesses the day-to-day variability in maximum and minimum temperatures. Historically, the standard deviation of daytime maximum temperature, averaged across the 14 Delaware weather stations, is almost 18°F, while the standard deviation of nighttime temperature is slightly lower, almost 17°F. In the future, the standard deviation of temperature is projected to change slightly: for maximum temperature, an increase

Figure 4.4 shows the historical and projected future range in temperature for each season. The largest and most significant change is in spring, where all models project a consistent increase in the range of temperature. Projected changes



Figure 4.4. Historical modeled and projected future temperature range (maximum - minimum temperature) for winter (Dec-Jan-Feb), spring (Mar-Apr-May), summer (Jun-Jul-Aug), and fall (Sept-Oct-Nov). Increases in the range are projected in spring, and decreases in fall. No change is projected in winter and summer, nor annually. Changes are the average for the state of Delaware, based on individual projections for 14 weather stations. Black “whiskers” indicate the range of scientific uncertainty from multiple climate models.

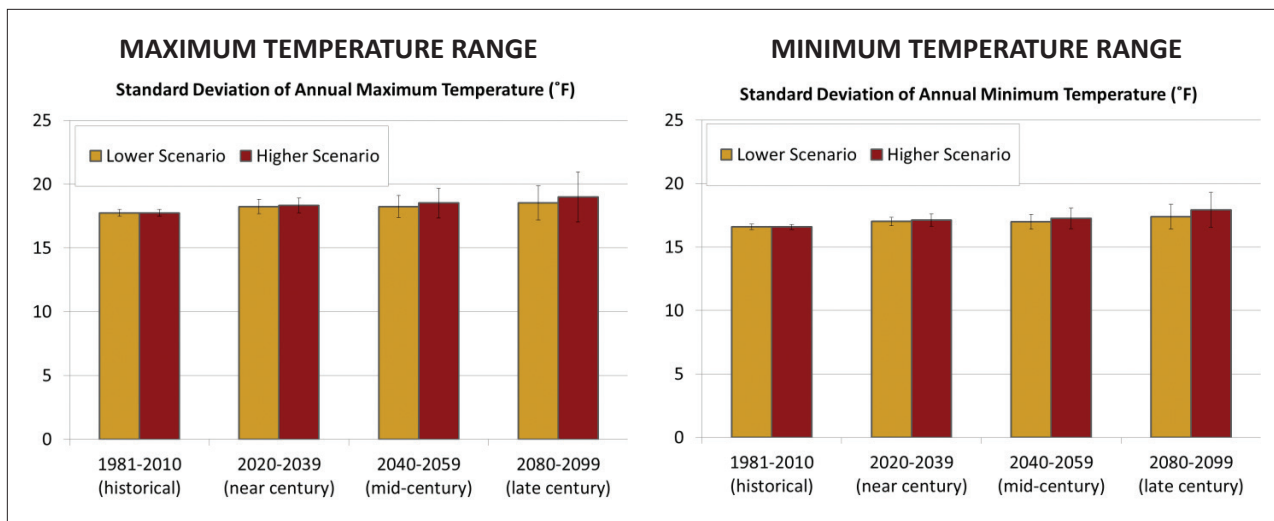


Figure 4.5. Historical and projected future **variability in day-to-day** annual maximum (daytime) and minimum (nighttime) temperature, **measured as the standard deviation** of daily values for each time period, in degrees F. Changes are the average for the state of Delaware, based on individual projections for 14 weather stations. The black “whiskers” indicate the scientific uncertainty that results from using multiple climate models.

of around 0.5°F under the lower scenario and 1°F under the higher scenario and for minimum temperature an increase of around 0.5°F under the lower scenario and 1.5°F under the higher scenario for the multi-model mean (**Figure 4.5**). Individual models do not necessarily agree: although the mean shows an increase, some models project no change or even a slight decrease. On average, this means that future climate change may increase the range in day-to-day temperatures as compared to the historical average, but this increase is not certain.

4.3.2. Temperature Extremes

As average maximum and minimum temperatures increase, extreme heat is also expected to become more frequent and more severe. Extreme cold is expected to become less frequent. What is viewed as “extreme” is often location-specific: while a 32°F or 90°F day may be extreme for one place, it may be normal for another. For that reason, a broad range of temperature extremes and thresholds were calculated: some using fixed thresholds (e.g., days per year over 100°F or below 32°F) and others using percentiles (e.g., future days per year colder than the coldest 1 percent of days, or warmer than the warmest 5 percent of days).

Beginning with percentiles, the temperature of the historical 1-in-100 (1 percent) and 1-in-20 (5 percent) coldest nights of the year currently averages around 18 to 19°F and 27 to 28°F, respectively. As average temperatures increase, the frequency of 1-in-20 coldest nights is projected to decrease from the historical average of 5 percent to 4 percent by 2020-2039, 3 percent by mid-century, and ultimately 2 percent by late-century, with slightly greater changes by late-century under the higher as compared to lower scenario (**Figure 4.6**, left). Little significant change is expected in 1-in-100 coldest nights, however. There is some indication of a small decrease in frequency, but it is not significant.

In terms of high temperatures, the temperature of the historical 1-in-20 (95 percent) and 1-in-100 (99 percent) hottest days averages around 80°F and 84-85°F, respectively. The frequency of 1-in-20 hottest days, currently 5 percent, is projected to increase to 7 to 11 percent by 2020-2039, 10 to 15 percent by mid-century, and around 15 percent under the lower scenario and more than 25 percent under the higher scenario by late-century (**Figure 4.6**, right). The frequency of the 1-in-100 hottest day, currently 1 percent, is projected to increase proportionally more to around 3 percent near-term, 6 percent by mid-century, and 5 to 10 percent under the lower

scenario and almost 20 percent under the higher scenario by late-century. In other words, the very coldest nights will still occur, but very hot days will become much more frequent, particularly the 1-in-100 hottest day, which could become as much as 20 times more frequent under the higher scenario by 2080-2099. This is consistent with an increase in the standard deviation of both maximum and minimum temperature discussed previously.

The two **cold temperature** thresholds examined here are the number of times per year when minimum (nighttime) temperatures fall below 20°F and below freezing, or 32°F. Historically, there are typically around 20 nights per year below 20°F and 85 nights per year below

freezing (**Figure 4.7**). In the future the number of times minimum temperature falls below 20°F is projected to drop by 5 days to an average of 15 by 2020-2039, by almost 5 more to an average of just over 10 times per year by 2040-2059, and to a minimum of 10 times per year under the lower scenario and only 3 to 4 times per year under the higher scenario by 2080-2099. In general, much larger changes in nights below 20°F are projected under the CMIP5 lower scenario (RCP 4.5) as compared to the CMIP3 lower scenario (B1), while projected changes under the two higher scenarios (RCP 8.5 and SRES A1fi) are similar.

The number of times minimum temperature drops below freezing is also expected to decrease: by

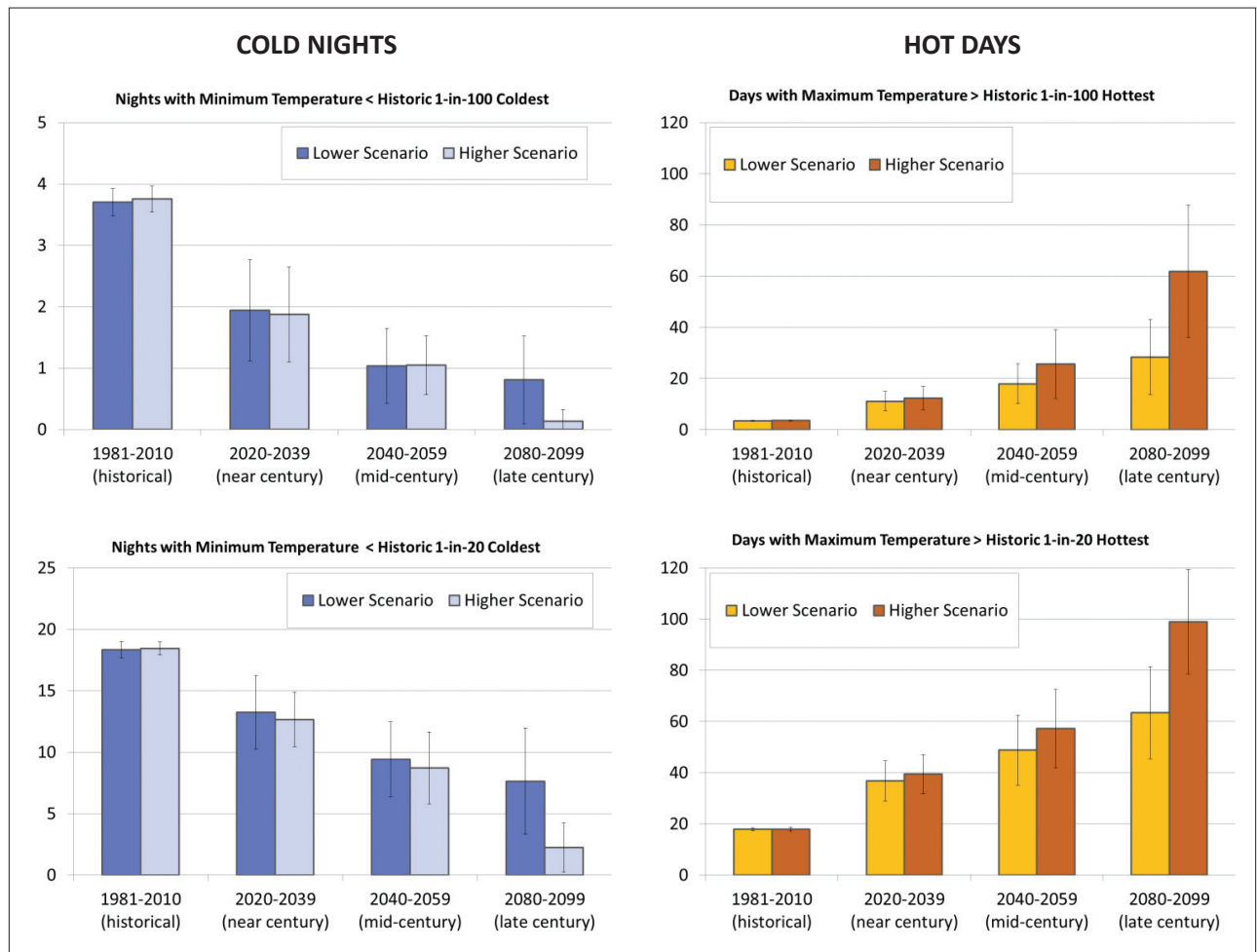


Figure 4.6. Projected number of **cold nights** (left) and **hot days** (right) that exceed the historical 1% (1-in-100 coldest), 5% (1-in-20 coldest), 95% (1-in-20 hottest), and 99% (1-in-100 hottest) days of the year. Changes are the average for the state of Delaware, based on individual projections for 14 weather stations. Black “whiskers” indicate the range of scientific uncertainty from multiple climate models.

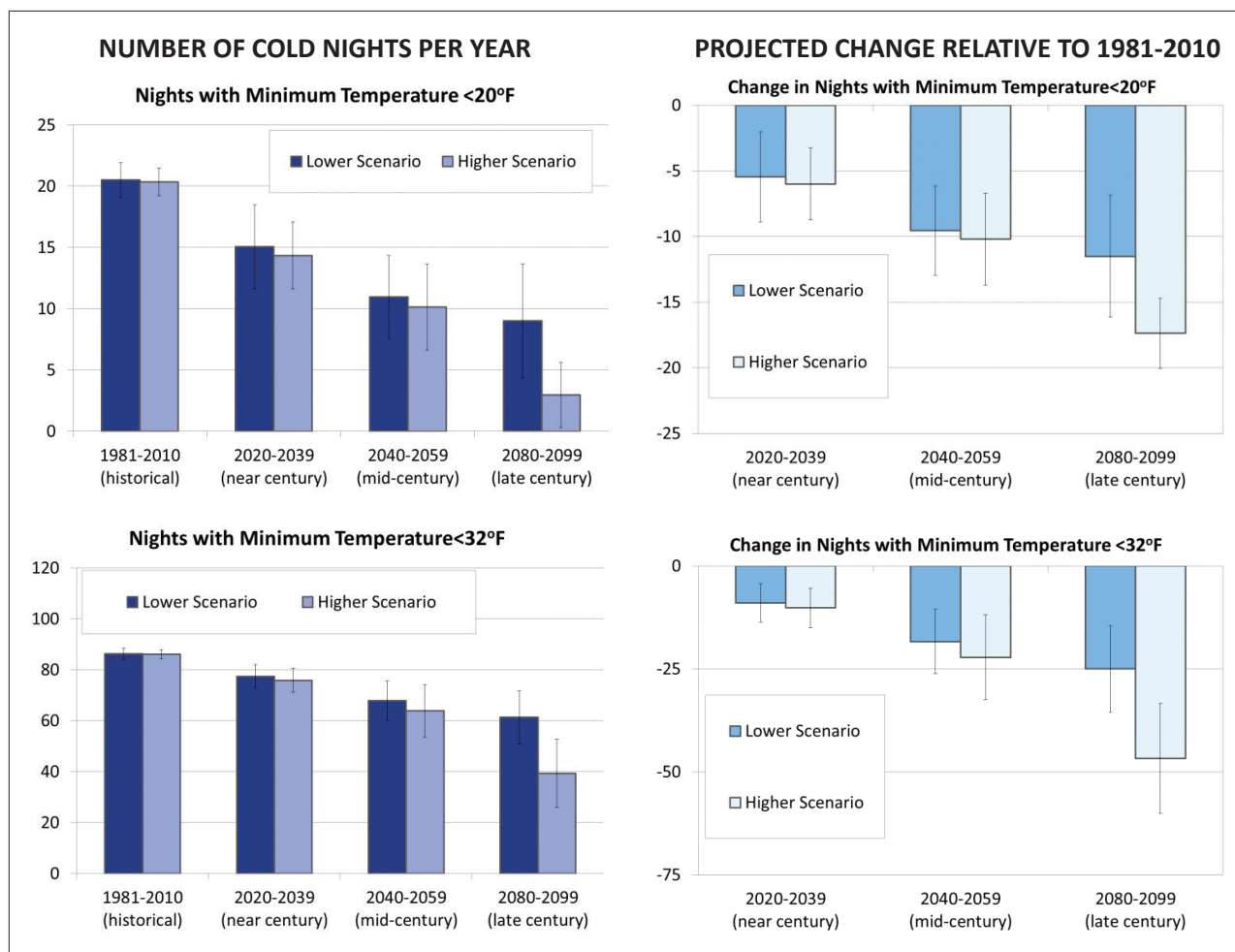


Figure 4.7. Historical and projected future number of **cold nights per year** (left) and projected change relative to 1981-2010 average (right) with minimum temperature below 20°F (top) and 32°F (bottom). Changes are the average for the state of Delaware, based on individual projections for 14 weather stations. Black “whiskers” indicate the scientific uncertainty that results from using multiple climate models.

around 10 nights near-term, and by 20 nights by mid-century (**Figure 4.7**). By late-century there are projected to be around 60 to 70 nights per year with below-freezing temperatures under the lower scenario and 40 to 50 nights per year under the higher scenario. For this threshold, greater changes tend to be projected under CMIP5 scenarios as compared to CMIP3.

The first and last dates of freeze each year are closely related to the length of the **growing season**. Although the growing season can be defined in different ways for different crops and various regions, it is defined here simply as the “frost-free” season, counting the number of days between the last frost in spring and the first frost in fall or winter. Across Delaware, the growing season currently averages around 210 days per

year. In the future, it is projected to lengthen: by about 10 days over the near-term, around 20 days by mid-century, and from 30 days under the lower scenario up to 50 days longer under the higher scenarios for late century (**Figures 4.8**).

For **high temperatures**, the days per year above four high temperature thresholds (95, 100, 105, and 110°F) are all projected to increase, with proportionally greater increases in the absolute number of days per year for the more extreme indicators (e.g., days over 105 or 110°F) as compared to the less extreme thresholds (e.g., 95°F; **Figure 4.9**). For example, Delaware currently experiences an average of less than 5 days per year with maximum temperature exceeding 95°F. By 2020-2039, that number of days is projected to increase to 10 to 15 per year. By mid-century, the

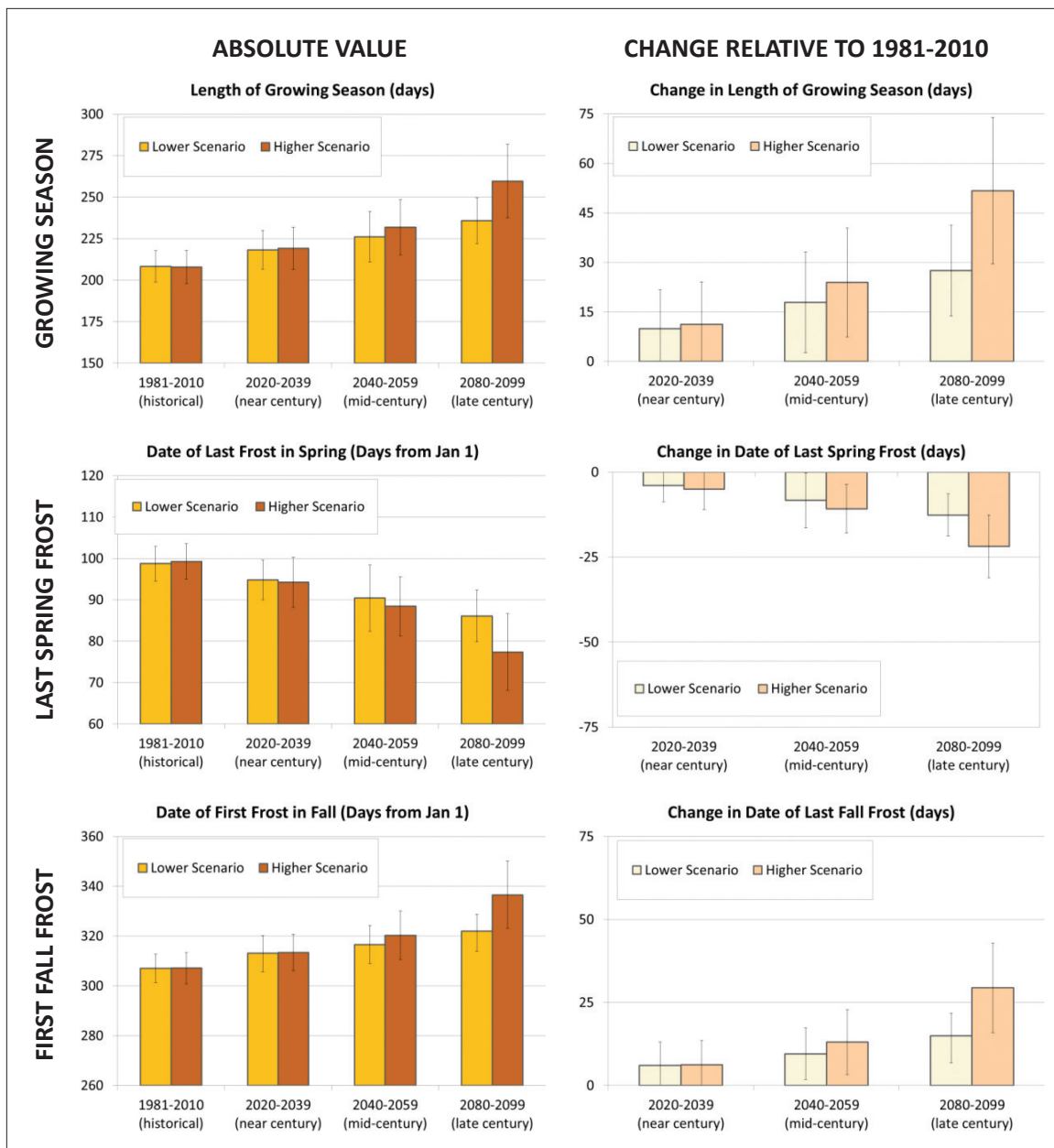


Figure 4.8. Projected absolute value (left) and change compared to 1981-2010 (right) in **growing season** (top), **date of last spring frost** (middle) and **first fall frost** (bottom). Greater changes are projected for spring and summer as compared to winter and fall. Changes are the average for the state of Delaware, based on individual projections for 14 weather stations. Black “whiskers” indicate the range of uncertainty from multiple climate models.

range increases to 15 to 30 days per year. By late-century, there could be an average of 20 to 30 days per year under the lower scenario and 50 to 65 days per year over 95°F under the higher scenario, an increase on the order of 4 to 6 times higher than historical values under the lower and more than 10 times historical values under the higher scenario. In contrast, a day over 100°F occurs only once every few years in the historical record. By 2020-2039 there are projected to be between

1 and 3 such days per year, and by 2040-2059, between 1.5 to 8 days per year. By late-century under the lower scenario there could be between 3 and 10 days per year over 100°F, an increase on the order of 10 to 30 times historical values; under the higher scenario, between 15 and 30 days per year. For maximum temperature extremes, CMIP5 projections are generally greater than CMIP3 under both higher and lower scenarios. For minimum temperature extremes, however,

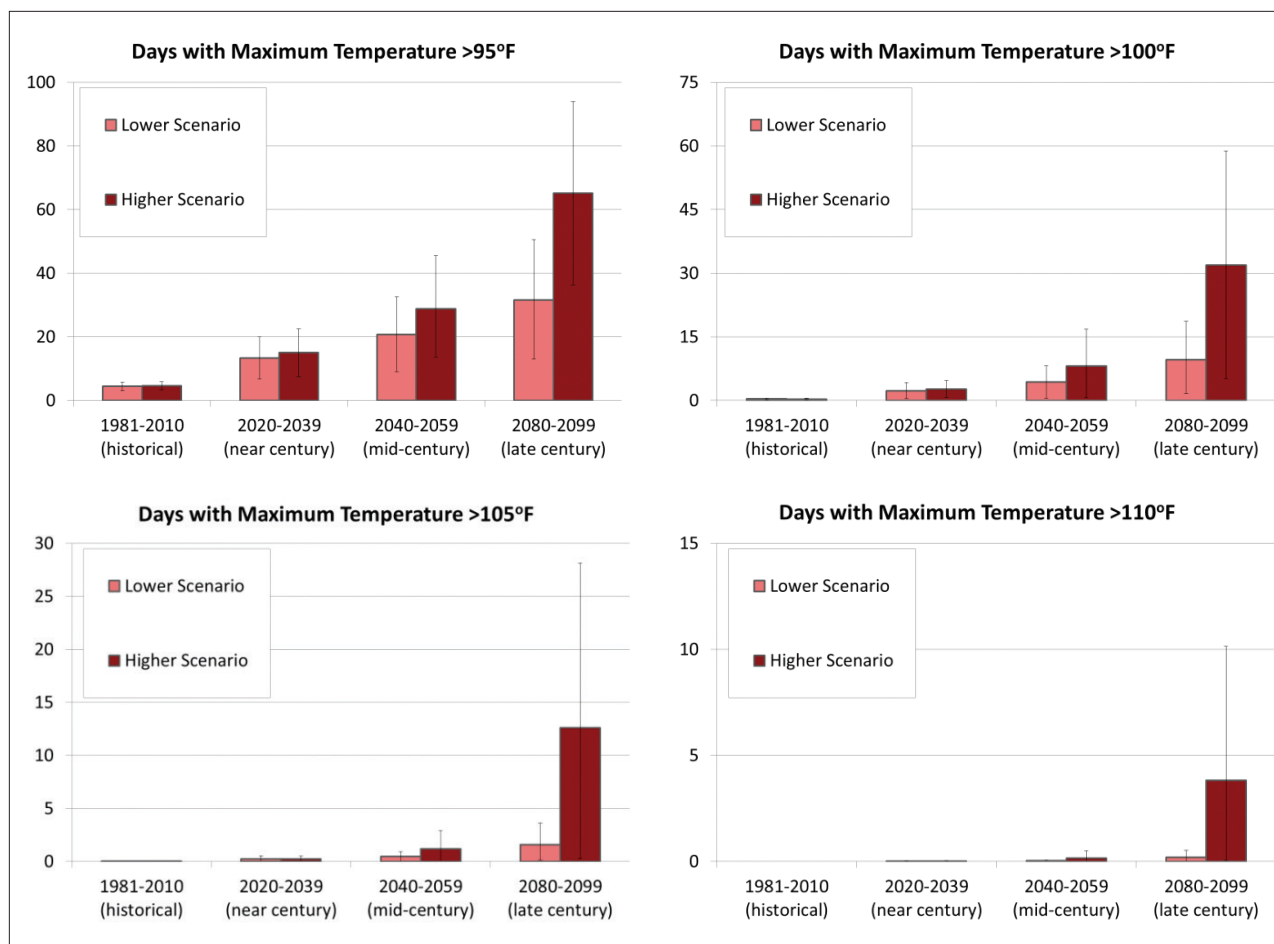


Figure 4.9. Historical and projected future number of days per year with maximum temperature above 95, 100, 105, and 110°F. Note different range on y-axis in each figure: from 0 to 100 days per year for 95°F to 0 to 15 days for 110°F. Changes are the average for the state of Delaware, based on individual projections for 14 weather stations. The black “whiskers” indicate the scientific uncertainty that results from using multiple climate models.

both CMIP3 and CMIP5 higher scenarios are noticeably and significantly higher than both CMIP3 and CMIP5 lower scenarios.

This analysis also calculated projected changes in three **minimum temperature** or **warm night** thresholds: the number of nights per year above 80, 85, and 90°F. Higher temperatures at night are often associated with health impacts, as warm nights offer no respite from high daytime temperatures. As with daytime maximum temperatures, the frequency of these nights is also projected to increase (**Figure 4.10**). Historically, nights over 80°F or higher are quite rare: averaged across the 14 weather stations used for this analysis, less than one per decade. In the future, an average of 3 nights per year above 80°F is projected for mid-century under the lower scenario, and 5 nights under the higher. By the end of the century,

projected changes range from 1 to 17 nights per year (with an average of 8) over 80°F in the lower scenario and between 10 and more than 50 nights per year (with an average of 32) under the higher scenario. Projected changes in the number of nights per year above 85°F and 90°F are around one-third and one-eighth as large, respectively, as the projected changes in nights per year over 80°F by late-century. The number of nights per year with minimum temperatures below the 1st and 5th percentiles of the distribution, and the number of days with maximum temperature above the 95th and 99th percentiles of the distribution were also calculated as part of this analysis (not shown). These projections are available in the Appendix.

Heat waves are another measure of extreme temperatures. Heat waves are generally defined as a period of prolonged, unusual heat. Here we

use four different definitions of heat waves to examine the difference in relatively mild versus more severe events. The first definition is the number of consecutive days with maximum daytime temperature exceeding 90°F (Figure 4.11). Historically, the longest stretch of back-to-back days exceeding 90°F averages around a week. This is projected to increase to 2 weeks by the near-term period of 2020-2039, 2½ to 3 weeks by mid-century, and almost 4 weeks under the lower scenario and more than 6 weeks under the higher scenario by late-century. The second and third definitions are similar: the longest stretch of days with maximum daytime temperature exceeding 95°F and 100°F. Historically, there are typically around 2 consecutive days over 95°F per year on average, but no more than one day over 100°F at a time. These numbers are also projected to increase. By late-century, the longest period of time over 95°F could average around 12 days under the lower and 25 days under the higher scenario by late-century. The longest period over 100°F could average around 4 days under the lower and 13 days under the higher scenario.

The definition of an extreme heat wave based on Kunkel et al. (1999; see key terms) is calculated based on the historical record of the strongest heat wave per decade. Historically, such events are rare, by definition. Near-term, heat waves (by this definition) are projected to occur on average every 3 out of 5 years. By mid-century, there could be an average of one event per year under the lower scenario and two per year under higher. By the end of the century, there are projected to be an average of 3 events per year under the lower scenario (with an uncertainty range from 1 to 5 per year) and 10 per year under the higher scenario (with an uncertainty range from 3 to 17). In other words, a heat wave that historically occurs only once per decade could be occurring 10 times per year by late-century.

4.3.3. Energy-Related Temperature Indicators

One of the many ways in which temperature increases can affect society and human systems is through changing the overall demand for energy,

including for heating energy in the winter and cooling energy in the summer. Across the United

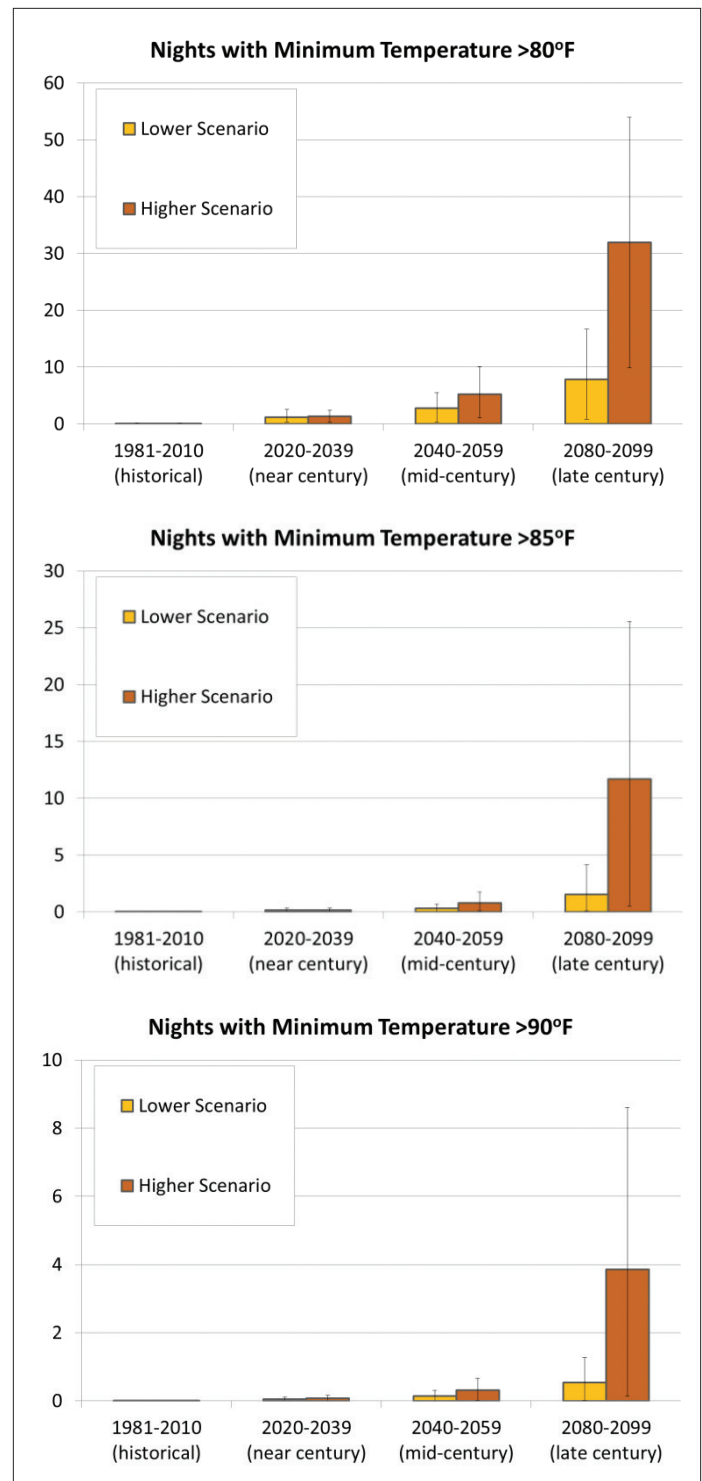


Figure 4.10. Historical and projected future number of nights per year with minimum temperature above 80, 85, and 90°F. Changes are the average for the state of Delaware, based on individual projections for 14 weather stations. Black “whiskers” indicate the scientific uncertainty that results from using multiple climate models.

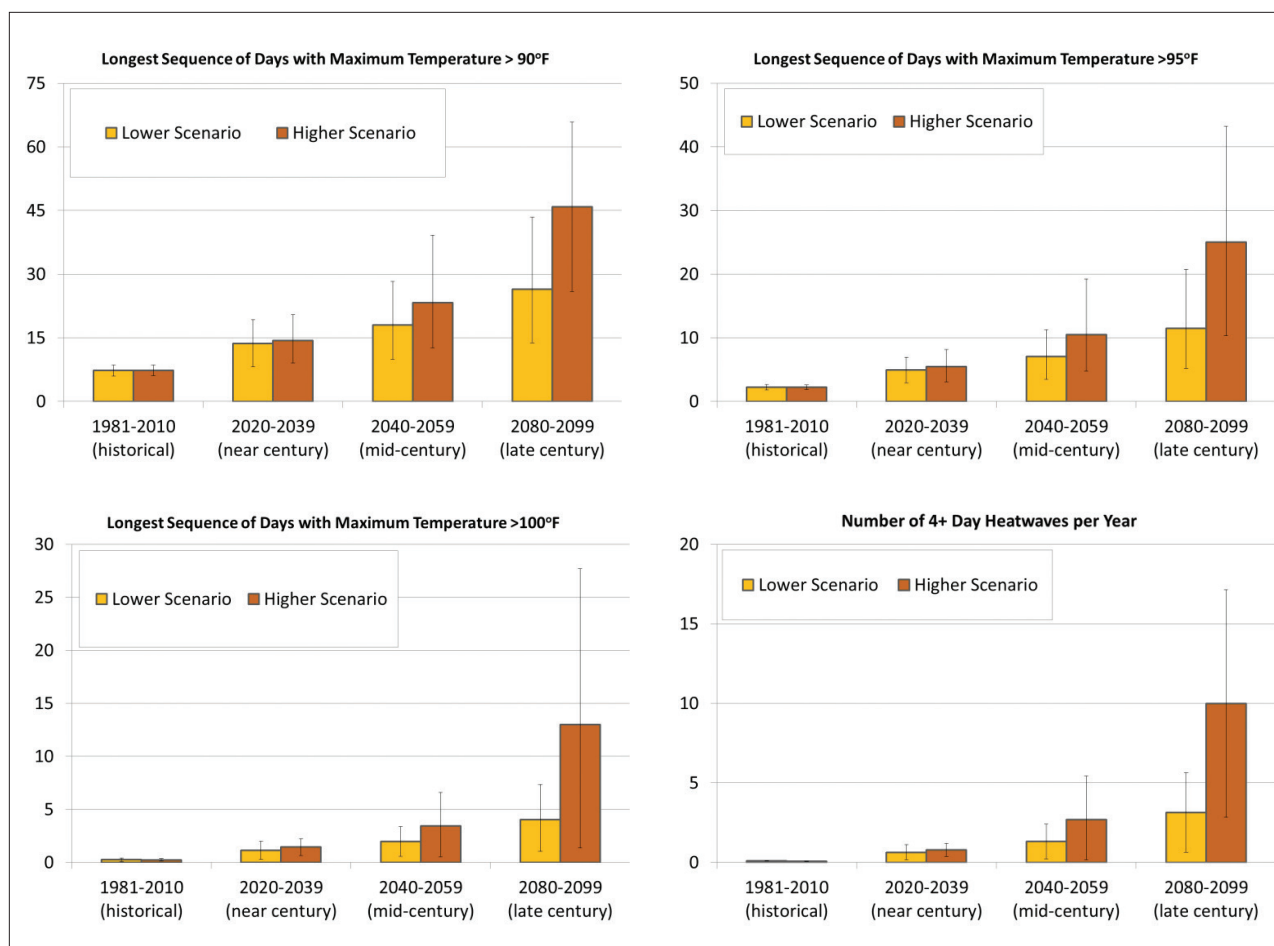


Figure 4.11. Historical and future **longest consecutive stretches of days with maximum daily temperature** exceeding 90, 95, and 100°F, and average number of extreme 1-in-10 year heat waves per year. Extreme heat waves are defined after Kunkel et al. (1999) as occurring on average once per decade during the historical period. Note different scales on y-axes of figures. Events are the average for the state of Delaware, based on individual projections for 14 weather stations. The black “whiskers” indicate the scientific uncertainty that results from using multiple climate models.

States, buildings account for approximately 40 percent of overall energy use, and most of that energy use consists of heating or cooling the interior space. Cooling and heating degree-days provide a useful indicator of demand for electricity in the summer (for air conditioning) and natural gas or oil in the winter (for space heating). They are typically calculated as the cumulative number of hours per year above (for cooling) or below (for heating) a given temperature threshold, here taken to be 65°F.

As temperatures increase, cooling degree-days and hence the demand for air conditioning in the summer are projected to increase; heating degree-days and demand for space heating will decrease. Currently, the annual average demand for cooling

across Delaware is relatively small (about 1,200 degree-days per year) compared to demand for heating (about 4,500 degree-days per year). As average and seasonal temperatures warm, demand for cooling will increase while demand for heating decreases. Under the higher scenario, by the end of the century, the demand for heating and cooling is projected to be approximately equal, around 3,000 degree-days per year (each, for heating and cooling). Under the lower scenario, demand for cooling is projected to be around two-thirds that of heating: 2,100 cooling degree-days per year as compared to around 3,500 heating degree-days per year.

This analysis makes no attempt to assess the ultimate impact on the consumer. It simply estimates projected changes in the demand for

cooling: a 30 percent increase by 2020-2039, a 35 to 70 percent increase by 2040-2059, and an average increase of 50 percent under the lower scenario and 130 percent under the higher scenario by late-century (**Figure 4.12**). Heating demand is projected to decrease: by about 10 percent near-term, nearly 20 percent by mid-century, and around 20 percent under the lower scenario and almost 40 percent by late-century. It is important to note, however, that the sources of energy for heating versus cooling are generally different (electricity versus gas or oil). For that reason, increases in cooling degree-days are not likely to be offset by decreases in heating degree-days but rather will have different impacts on energy supply and costs.

4.4. Precipitation-Related Indicators

As the earth warms, precipitation patterns are also expected to shift in both space and time. Some seasons may get wetter, while others get drier. The intensity and frequency of heavy rainfall, as well as the duration of dry periods, may be altered. Mid-latitudes are generally projected to become wetter, with increases in heavy precipitation events. Across the Northeast and Mid-Atlantic region, heavy precipitation has already increased – by more

than 70 percent over the last 60 years, in many locations, according to the Third U.S. National Climate Assessment.¹⁶

This section summarizes the changes in precipitation and related secondary indicators that are projected to occur in response to global climate change.

4.4.1. Annual and Seasonal Precipitation

Annual precipitation across Delaware averages around 45 inches per year. It is evenly distributed throughout the year, with more than 10 inches on average falling in each season. Slightly less precipitation (around 1 to 2 inches less) tends to fall in fall and winter as compared to spring and summer.

In the future, annual average precipitation is projected to increase (**Figure 4.13**), consistent with a general increase in precipitation projected for mid-latitudes, including the northern half of the United States. Increases are greater and more consistent by late-century compared to earlier time periods. For both the near-term and mid-century periods, for example, the multi-model average shows an increase in precipitation under all scenarios, but some individual model simulations show decreases. By late-century, in contrast, all but one model

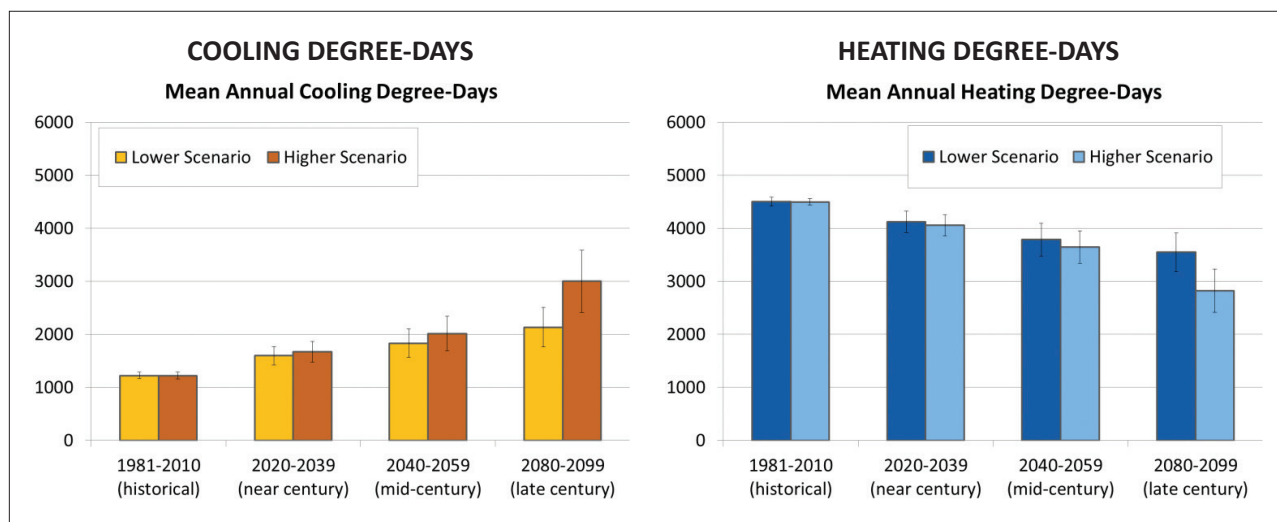


Figure 4.12. Historical and projected future annual cumulative **cooling and heating degree-days** using a temperature threshold of 65°F. Changes are the average for the state of Delaware, based on individual projections for 14 weather stations. Projected changes under the lower scenario are shown in yellow for cooling degree-days (which are warm) and dark blue for heating degree-days (which are cold). The black “whiskers” indicate the uncertainty that results from using multiple climate models.

shows an increase, as indicated by the black bars in **Figure 4.13**. There is a small and, given the range of uncertainty, likely insignificant difference between the amount of increase projected to occur under the higher versus lower scenario. Projected increases under CMIP3 simulations tend to be slightly higher than under CMIP5 simulations (10 to 20 percent versus 7 to 10 percent, respectively, by late-century; not shown here).

Seasonal changes show stronger differences between scenarios for projected precipitation increases in winter (**Figure 4.14**). In winter, when the largest precipitation increases are projected to occur, increases projected under a higher scenario are higher by late-century than under a lower scenario. Projected changes in spring, summer, and fall precipitation do not show significant scenario differences (or much change at all, as the ranges of uncertainty for each multi-model average all encompass both positive and negative changes, even out to the end of the century; **Figure 4.14**, right side).

The seasonality of changes in precipitation is a key area where older CMIP3 simulations (based on four global climate models) differ from newer CMIP5 simulations (based on nine global climate models). CMIP3 projections show increases in precipitation to be distributed evenly throughout the year. In contrast, CMIP5 shows precipitation increases only in winter and fall. In addition to

seasonal changes in precipitation, changes in 3-month, 6-month, and 12-month cumulative precipitation were calculated for periods beginning with each month from January to December. These results are available in the Appendix.

4.4.2. Dry and Wet Periods

As climate changes, precipitation is projected to increase, particularly in winter. However, little to no change is projected in annual dry days. This can be explained by the increase in precipitation intensity. Although there is more precipitation, the average amount of precipitation falling on wet days is also increasing: by around 2 percent over the near term, 3 to 4 percent by mid-century, and 5 percent under a lower scenario and 11 percent under a higher scenario by the end of the century. This increase in the average amount of precipitation falling on a given wet day keeps pace with the projected increase in winter precipitation. Thus, little to no change in dry days is projected (**Figure 4.15**). The total number of dry days per year is another variable on which CMIP3 and CMIP5 projections for the future disagree slightly. Under CMIP3, the number of dry days is projected to decrease by a few days a year. This small difference is likely the result of projected increases in annual precipitation under CMIP3 being slightly larger than projected increases under CMIP5; simply put, with that

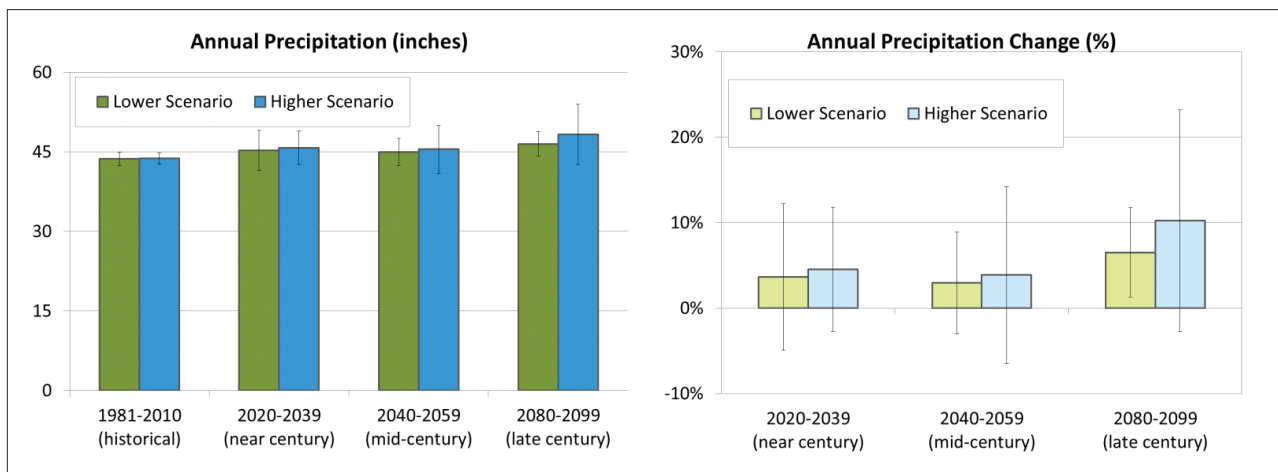


Figure 4.13. Historical and future simulated annual average precipitation (left) and change in annual average precipitation (right) as simulated under a lower (green) and higher (blue) future scenario. Changes are the average for the state of Delaware, based on individual projections for 14 weather stations. The black “whiskers” indicate the uncertainty that results from using multiple climate models.

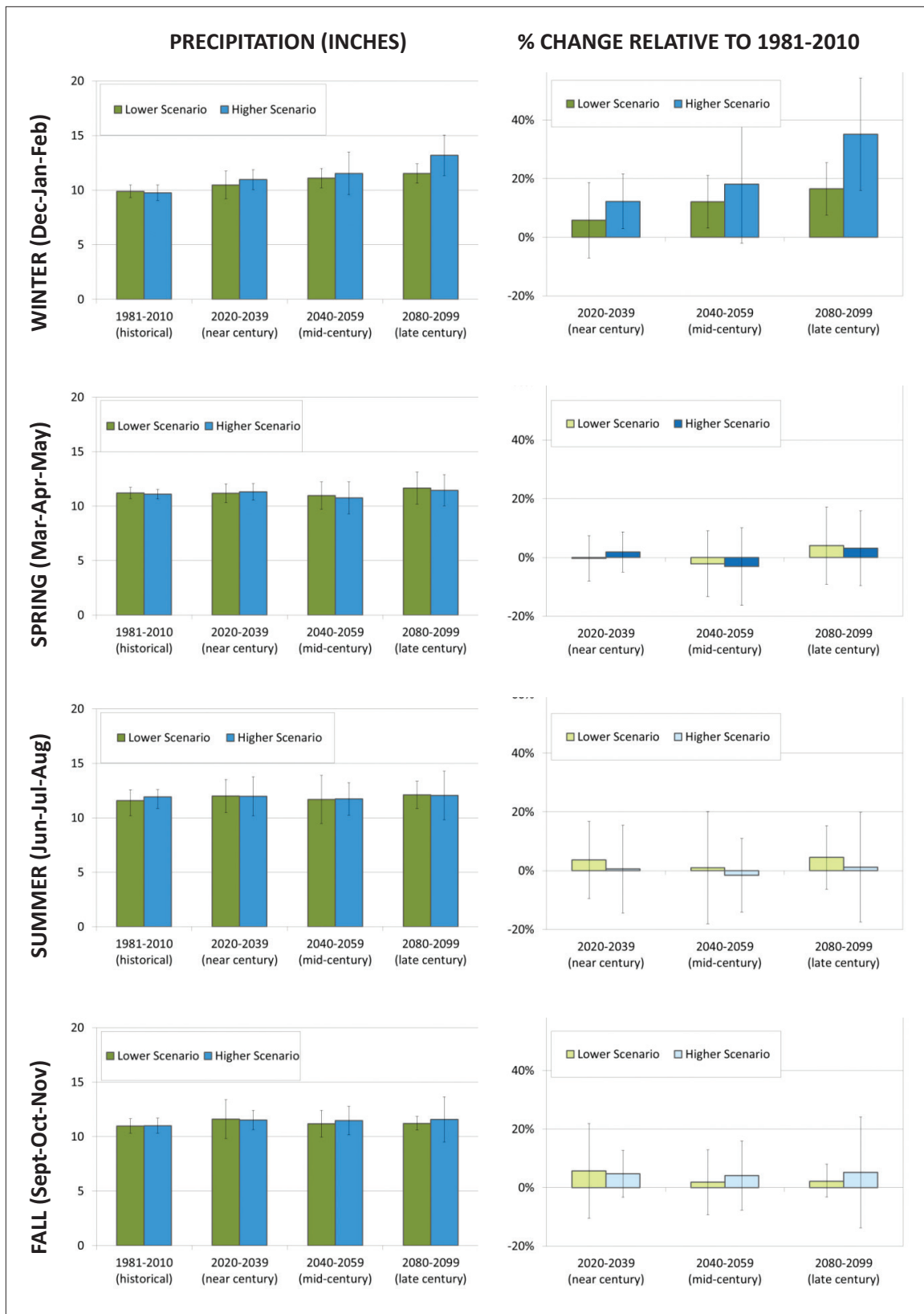


Figure 4.14. Historical and future cumulative seasonal precipitation (left) and percentage change in cumulative precipitation compared to 1981-2010 (right) for winter (Dec-Jan-Feb), spring (Mar-Apr-May), summer (Jun-Jul-Aug), and fall (Sept-Oct-Nov). Greater changes are projected for winter and fall, little change in spring and summer. Changes are the average for the state of Delaware, based on individual projections for 14 weather stations. Black “whiskers” indicate the range of scientific uncertainty from multiple climate models.

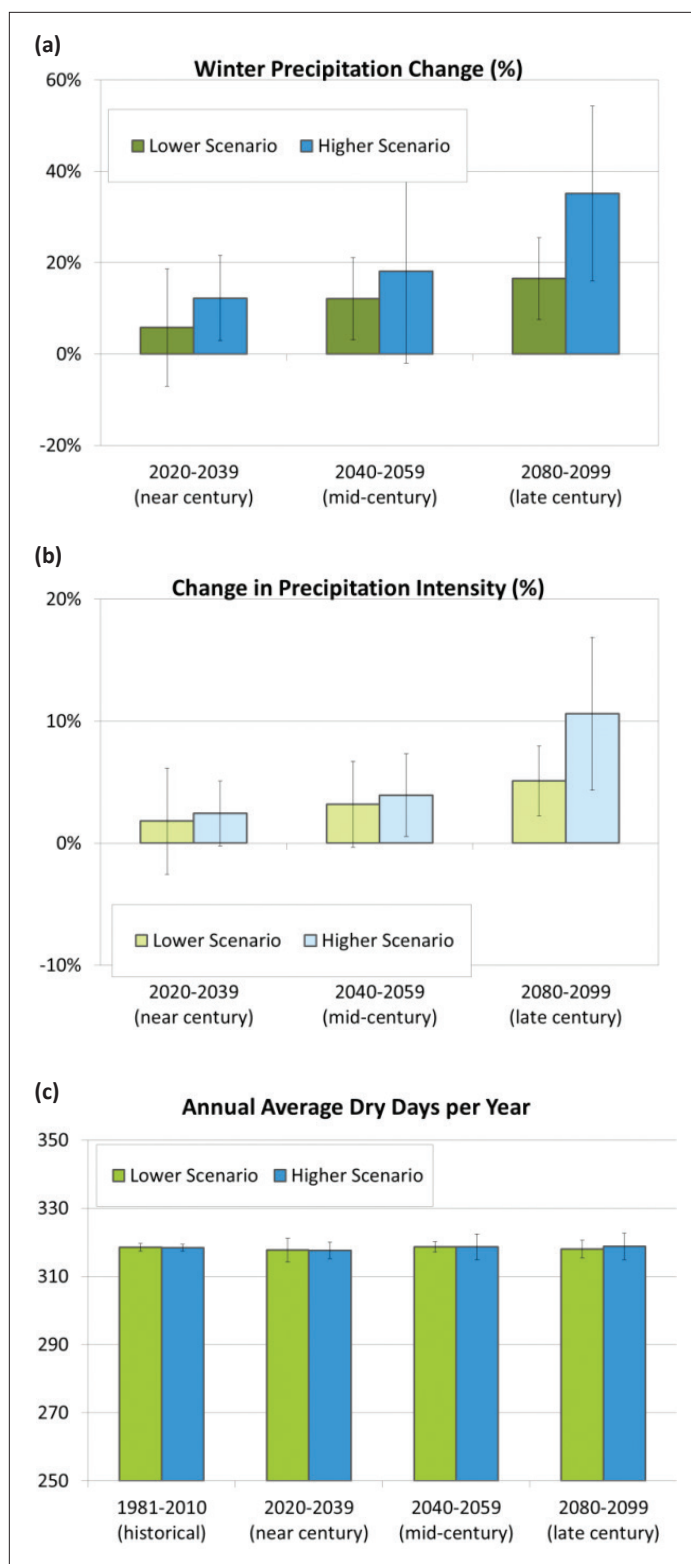


Figure 4.15. Historical and future percentage changes in (a) winter precipitation and (b) precipitation intensity balance out to suggest little change in (c) the overall number of dry days per year. Changes are the average for the state of Delaware, based on individual projections for 14 weather stations. Black “whiskers” indicate the range of scientific uncertainty from multiple climate models.

much more rain, there are a few more wet days each year.

The Standardized Precipitation Index (SPI) offers a different way to look at dry and wet conditions. This index is commonly used by the National Drought Mitigation Center and the National Climatic Data Center to indicate dry and wet areas within the continental United States on an ongoing basis. It is standardized, such that zero represents normal conditions for that location; negative values indicate conditions drier than average, from 0 to -7, while positive values indicate wetter conditions, from 0 to +7. Projections suggest a trend towards slightly wetter conditions, with average SPI increasing by 0.1 over the course of this century, consistent with increases in average precipitation (not shown; figure available in the Appendix). However, given an index from 0 to 7, this increase is very small and the uncertainty range due to multiple models encompasses zero, suggesting that some models project a slight decrease in SPI and others, an increase and overall, results are not very significant.

4.4.3. Heavy Precipitation Events

Heavy precipitation events are already increasing globally, across the United States, and across the northeast region of the United States in particular. The increased frequency of these events has been formally attributed to human-induced climate change. In many regions, the observed trend in heavy rainfall is expected to continue in the future as warming temperatures accelerate the hydrologic cycle at both the local and global scale.¹⁷

National and global studies typically look at heavy precipitation over a single range; however, depending on the region, different levels of heavy snow and rain can have very different impacts. Here, a broad range of precipitation indicators were analyzed. They consist of:

- Number of days per year with more than 0.5, 1, 2, 3, 4, 5, 6, 7 and 8 inches of precipitation in 24 hours;
- The wettest day, 5 days, and 2 weeks in 1, 2, and 10 years; and

- Number of days per year exceeding the historical 2-, 4-, and 7-day maximum rainfall

For the state of Delaware, nearly every indicator of extreme precipitation is projected to increase in the future (**Table 4.1**). This is consistent with observed trends as well as with future projected trends across the eastern United States. For “less extreme” indicators (e.g., days per year over 0.5 or 1 inches in 24 hours), there was little difference in projected changes under the higher versus

lower scenario, although overall larger changes are projected by late-century as compared to near-term. For “more extreme” indicators (e.g., days per year with 2 inches or more of precipitation in 24 hours), projected changes under the higher scenario were generally greater than projected changes under the lower scenario, although in all cases the range of uncertainty due to using multiple model projections continues to overlap, suggesting that the differences between scenarios may not be statistically significant. For “very extreme”

Table 4.1. Other projected changes in **indicators of extreme precipitation** calculated in this analysis include: (1) the average number of days per year where cumulative precipitation exceeds thresholds between 0.5 and 8 inches; the total amount of precipitation falling in the wettest 1, 5, and 14 consecutive days of (2) the year, (3) 2 years, and (4) 10 years; and (5) the number of times per year the historical 2-, 4- and 7-day maximum precipitation amounts are exceeded in the future.

	1981-2010	2020-2039	2040-2059		2080-2099	
			Lower	Higher	Lower	Higher
(1) Days per year exceeding a given threshold of 24-hour cumulative precipitation						
0.5	28.1	29	28.6	28.6	29.3	29.6
1	12.0	12.9	12.9	13.1	13.6	14.7
2	2.1	2.5	2.5	2.7	2.7	3.4
3	0.7	0.8	0.8	0.8	0.9	1.2
4	0.3	0.3	0.4	0.4	0.4	0.55
5	0.1	0.2	0.2	0.2	0.2	0.29
6	0.1	0.10	0.10	0.10	0.14	0.18
7	0.04	0.06	0.07	0.07	0.09	0.13
8	0.03	0.04	0.04	0.05	0.07	0.10
(2) In one year, wettest ...						
1 day	3.3	3.5	3.5	3.6	3.8	4.2
5 days	6.4	6.6	6.7	6.8	7.1	7.4
2 weeks	14.2	14.3	14.3	14.4	14.5	14.5
(3) In 2 years, wettest ...						
1 day	4.1	4.3	4.3	4.6	4.9	5.4
5 days	7.4	7.7	7.8	8.3	8.8	9.0
2 weeks	14.4	14.5	14.6	14.7	15.2	15.1
(4) In 10 years, wettest ...						
1 day	6.2	6.7	6.7	7.1	8.1	8.6
5 days	10.7	11.1	11.4	12.7	14.3	13.3
2 weeks	15.7	15.9	16.4	17.3	18.7	17.9
Number of times historical threshold is exceeded						
2-day maximum	0.001	0.013	0.011	0.019	0.019	0.046
4-day maximum	0.000	0.005	0.005	0.013	0.008	0.024
7-day maximum	0.000	0.003	0.001	0.009	0.004	0.015

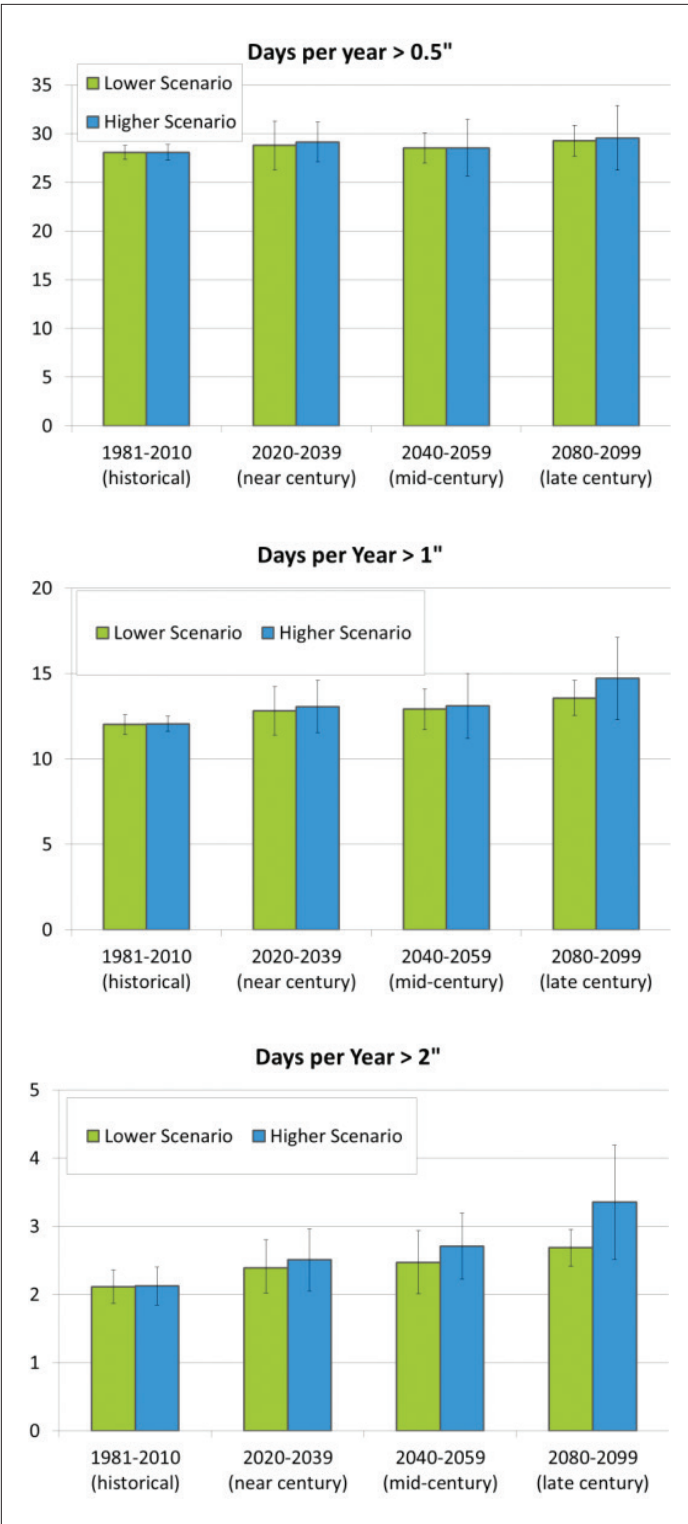


Table 4.16. Projected future changes in the number of days per year with **cumulative precipitation** exceeding a range of thresholds from 0.5 to 2 inches in 24 hours. Changes are the average for the state of Delaware, based on individual projections for 14 weather stations. Projections using the lower future scenario are green; the higher scenario, blue. Black “whiskers” indicate the scientific uncertainty that results from using multiple climate models.

indicators (e.g., wettest 1 or 5 days of the year or beyond), there was less of a difference between higher versus lower scenarios. Finally, the amount of precipitation falling in the wettest 2 weeks of the year (or 2 years, or 10 years) showed little to no change over any time frame. This suggests that the largest impact of climate change will be on short-duration precipitation events, which can be both convective and large-scale in nature, rather than on the frequency and duration of large weather systems that bring extended rain over multiple weeks.

In terms of thresholds, precipitation records across 14 Delaware stations shows that, on average, the state currently experiences around 28 days per year with more than 0.5 inches of rain in 24 hours; 12 days with more than 1 inch; and 2 days with more than 2 inches. By late-century, these numbers are projected to increase by 1 to 2 days for 0.5 inches, 2 to 3 days for 1 inch, and an average of 0.5 to 1 day per year for 2 inches (Figure 4.16). Additional changes projected for other indicators are listed in **Table 4.1**.

For lower amounts of heavy precipitation (0.5 to 2 inches in 24 hours), projected changes under CMIP3 are generally greater than under CMIP5, likely because CMIP3 models project larger increases in average precipitation as compared to CMIP5. For higher levels of precipitation (3 to 8 inches), however, CMIP3 and CMIP5 projections are similar.

4.5. Hybrid Variables

Temperature and precipitation alone do not capture the full extent of relevant change in Delaware’s climate. For that reason, this report also presents projected changes in humidity and in “hybrid” or multivariable indicators such as heat index (a combination of temperature and humidity that measures how hot it “feels” to the human body), potential evapotranspiration (which depends on solar radiation, humidity, temperature, winds, and other factors), and cool and wet or hot and dry days.

4.5.1. Relative Humidity and Dewpoint Temperature

Figure 4.17 compares projected changes in dew point temperature (defined as the temperature

to which the air must be cooled to condense the water vapor it contains into water) with projected changes in average temperature by season, compared to the 1981-2010 average. In general, projected changes for dew point temperature are similar to and slightly less than those projected for average temperature. This could be the result of small decreases in relative humidity projected for most seasons except spring (not shown; available in the Appendix). However, it could also be related to the fact that dew point temperature projections could be calculated only for three airport locations with long-term humidity records.

4.5.2. Summer Heat Index and Potential Evapotranspiration

Heat index is often used in the summer to express

how hot it “feels” to the human body, based on a combination of both temperature and humidity, which affects evaporation and cooling. A related metric is potential evapotranspiration, or PET. This measures the amount of evaporation that would occur, given certain levels of temperature, wind, humidity, and solar radiation, and an unlimited water supply.

The relationships among heat index, temperature, and humidity are not linear. Despite little change to a slight decrease being projected for relative humidity in summer (Figure 4.18), projected increases in summer heat index by the end of the century are approximately double the projected changes for maximum daytime summer temperature alone. In other words, the projected increase in temperature may *feel* twice as large

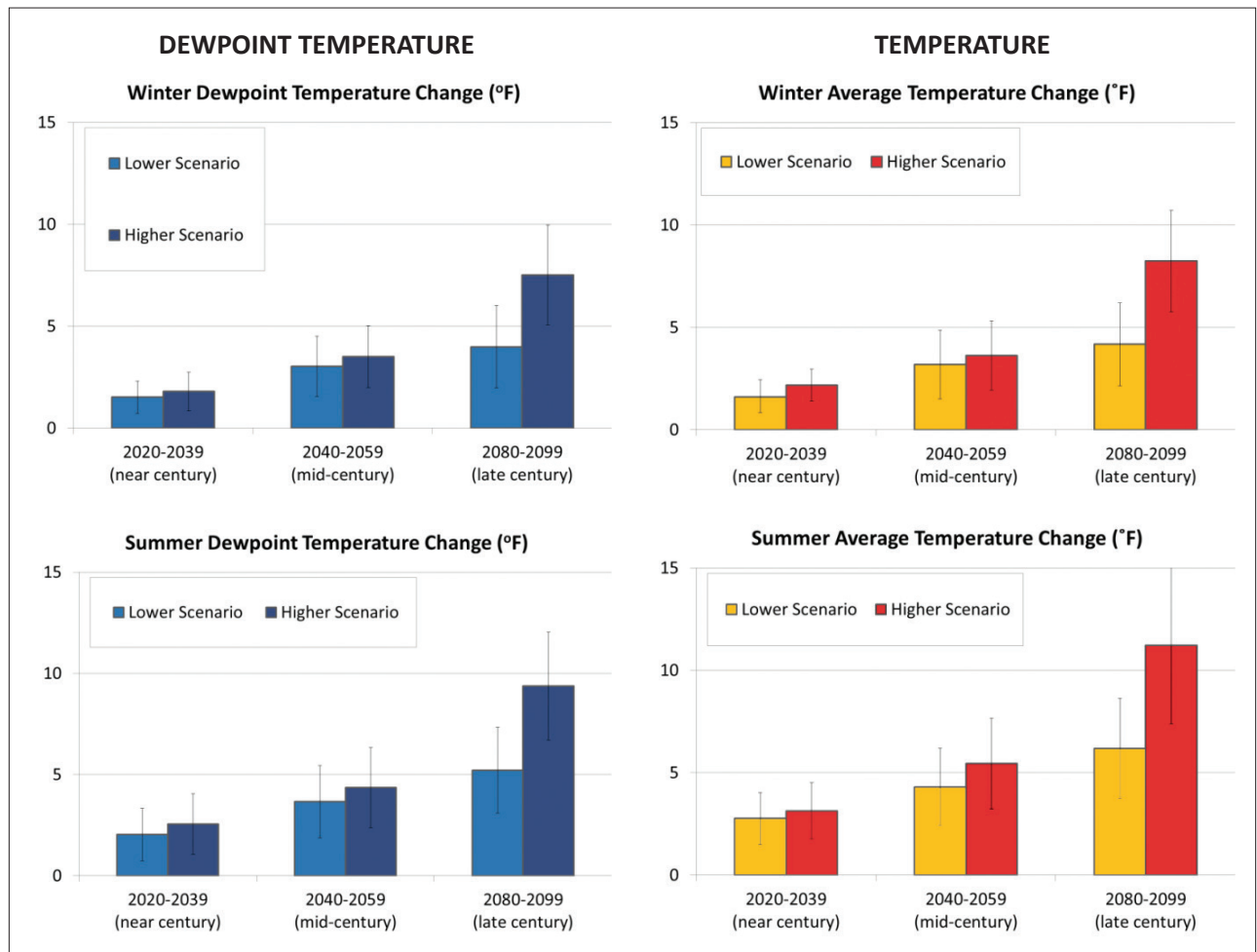


Figure 4.17. Historical simulated and future projected precipitation amounts in **dew point temperature** (left) and average temperature (right) for winter and summer. (Spring and fall graphs provided in the Appendix.) Dew point temperatures are based on projections for three airport locations only; average temperatures are based on projections for all 14 weather stations. The black “whiskers” indicate the uncertainty that results from using multiple climate models.

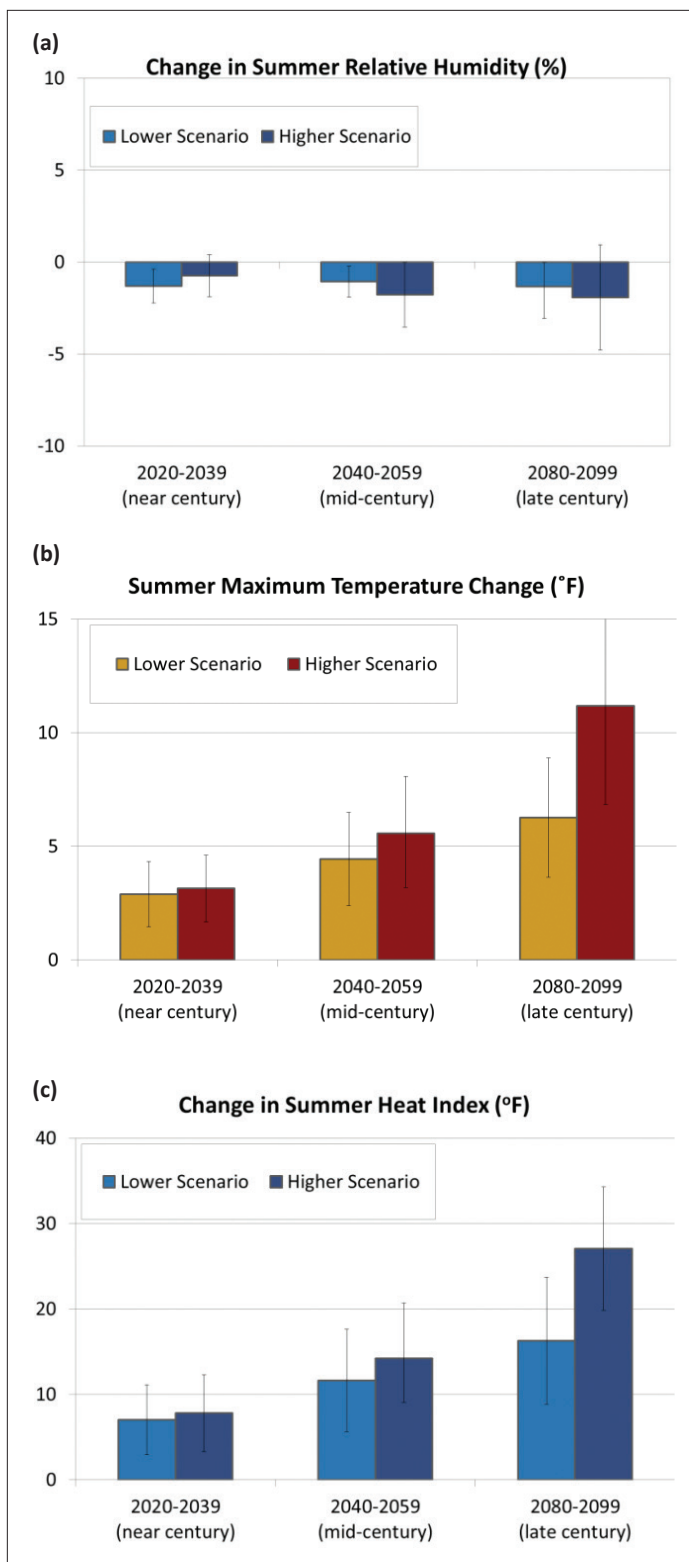


Figure 4.18. Historical simulated and future projected changes in summer (June, July and August) **(a) relative humidity, (b) maximum temperature, and (c) heat index.** Projections in (a) and (c) are based on 3 airport locations only; average temperatures in (b) are based on projections for all 14 weather stations. The black “whiskers” indicate the scientific uncertainty that results from using multiple climate models.

as it actually is, due to the interactions between humidity and temperature.

Evaporation is projected to increase, primarily driven by increases in temperature. The largest increases are projected for summer, followed by spring and fall (**Figure 4.19**).

4.5.3. Hybrid Temperature and Precipitation Indicators

The final set of hybrid indicators focuses on the combination of temperature and precipitation. The number of “hot dry” days with maximum temperatures over 90°F without measurable rain is projected to increase 50 to 100 percent over the near term. By late-century there could be between two and more than four times more hot/dry days (**Figure 4.20**) compared to the 1981-2010 average, depending on which scenario is more likely. In contrast, the number of “cool wet” days with maximum temperatures below 65°F and measurable precipitation is projected to decrease, but not by much. Slightly greater changes are projected under the higher (4 to 6 days) as compared to the lower (1 to 2 days) scenario by the end of the century. The amount of precipitation that falls as rain rather than snow is already quite high for Delaware, around 98 to 99 percent. In the future, slightly more precipitation is projected to fall as rain than snow as temperatures warm; however, this is not likely to have a significant impact, because it amounts to a change of only 1 to 2 percent (not shown – see Appendix).

4.6. Conclusions

Climate change is expected to affect Delaware and the surrounding region by increasing average, seasonal, and extreme temperatures, as well as increasing average precipitation, increasing the frequency of heavy precipitation events, and increasing the total amount of rainfall that falls in the wettest periods of the year.

For all temperature-related indices, there is a significant difference between the changes expected under the higher as compared to lower

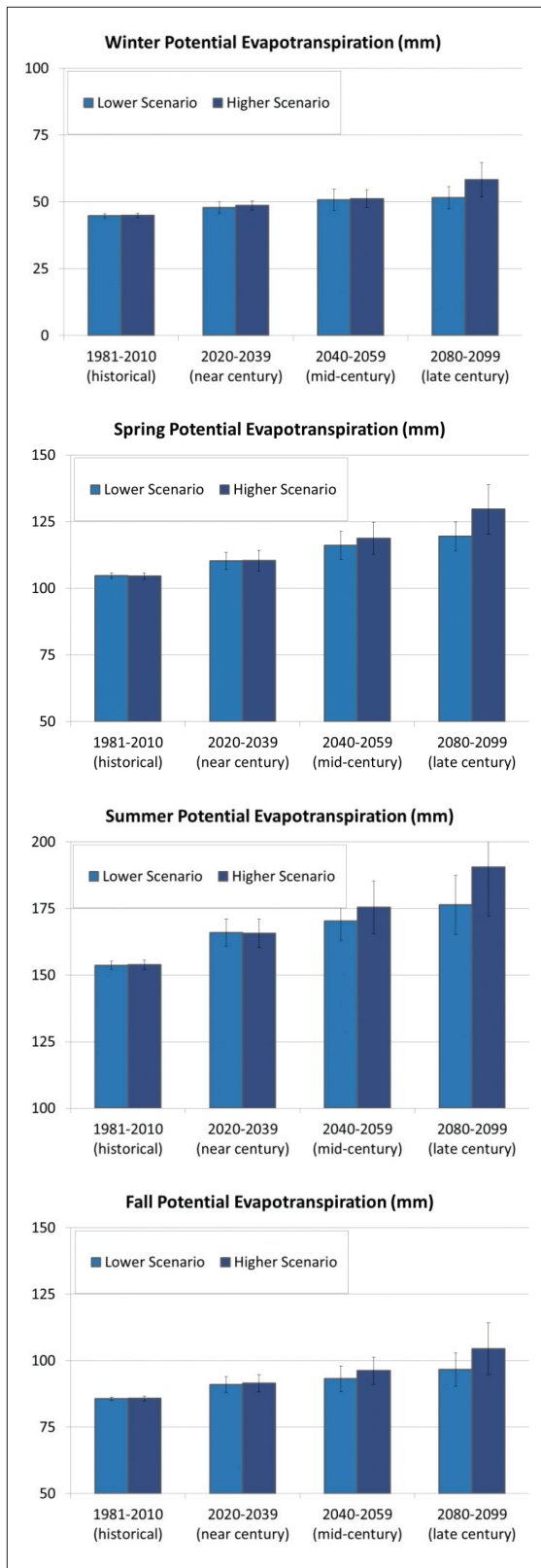


Figure 4.19. Historical simulated and future projected changes in **seasonal potential evapotranspiration (PET)**. Although the y-axis of the plots covers a different range, the total range covered is identical (100 mm), so relative changes can be seen from one season to the next.

scenario by late-century. For many of them, this difference begins to emerge by mid-century.

The projections described here underline the value in preparing to adapt to the changes that cannot be avoided. Changes that likely cannot be avoided would include most changes in precipitation and, at minimum, the temperature-related changes projected to occur over the next few decades, and under the B1 or RCP 4.5 lower scenarios. However, immediate and committed action to reduce emissions may keep temperatures at or below those projected under the lower scenario. Thus, the larger temperature impacts projected under the higher A1FI or RCP 8.5 scenarios can be avoided by concerted mitigation efforts. The greater the reduction in climate forcing from human activities, the more possible it will be to successfully adapt to a changing climate.

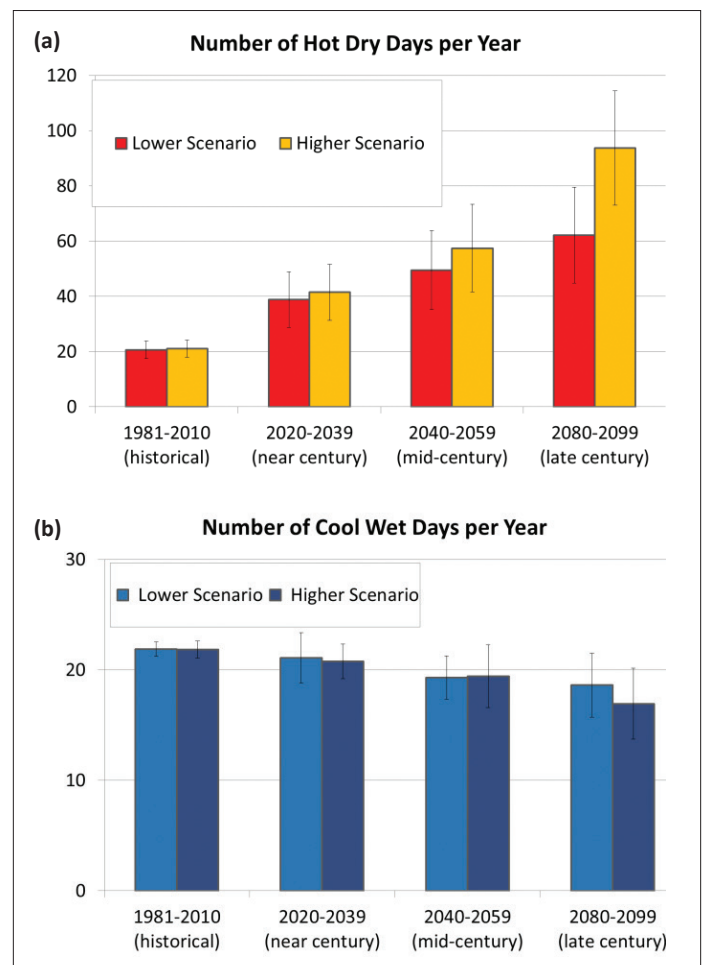


Figure 4.20. Historical simulated and future projected changes in (a) the number of **hot dry days** with no precipitation and (b) **cool wet days** with precipitation.

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